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The Comparison of Calculated and Experimental Values for the Dielectric Constant of Powdered Solids

By

Brother Gerard Znider F.S.C.

A Thesis
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Approved

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147000

Dr. D. McKenney

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ABSTRACT

The dielectric constant of glass beads of various sizes, ground glass, Ca CO_3, and Ba SO_4 has been determined in this laboratory by the method of mixtures.

The experimental values were compared to calculated ones which were obtained by employing various semi-empirical and empirical equations which relate the effective dielectric constant of a powder, the volume fraction and the dielectric constant of the continuous medium to the dielectric constant of the solid comprising the powder.

ACKNOWLEDGEMENTS

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To the University of Windsor, for a laboratory assistantship and to the National Research Council for a Postgraduate Scholarship, I express my heartfelt thanks.

TABLE OF SYMBOLS

Symbol	Page	Definition of Symbol
ε_m	1 - 69	observed dielectric constant
ε_1	1 - 69	dielectric constant of material comprising the powder
ε_2	1 - 69	in a suspension or heterogenious mixture, the dielectric constant of the liquid phase
d	3	distance between condenser plates
A	3	surface area
σ	3	charge per unit area
E	3	electric field
D	4	electric displacement
P	3, 4	polarization
V	4	volume
M	4	dipole moment
d	5	density
M	5	molecular weight
	1 - 69	volume fraction of the solid comprising the powder
μ	6, 9	empirical quantity
f	7, 8	form factor
A_i	8	dipolarization factor
v	9,10,36,37,38,65	empirical quantity
K	10,36,37,38,43,44 appendix	empirical quantity
f_1 f_2	10, 11	field ratios
a, b	13	empirical constants
K	26,27,28,32,33,34	dielectric constant of a sample

CHAPTER I

INTRODUCTION

A General Considerations:

The dielectric constant has been measured for almost all of the pure liquids that one employs in chemical and physical research. The same cannot be said of solids. The drawback incurred in this study is an experimental one. It is very difficult to obtain a reliable value for the dielectric constant of a solid. To date, the dielectric constant of a solid has been measured by using four methods. However, each method has its disadvantages that make the measurement either impractical or impossible.

The most reliable and the method employed by most has been a capacity measurement of large, flat-ground discs of single crystals, placed between metal electrodes. However, it is difficult to obtain the exact measurements of the physical dimensions of the crystal. There is an uncertainty about the edge correction terms in Kirchoff's formula. The greatest difficulty is experienced in obtaining flawless crystals, large enough to be ground into discs.

The use of compressed powdered crystals has also been investigated, but this method has its problems also. The greatest difficulty here is the introduction of a correction that must be made to account for the small amount of air space, still enclosed in the compressed powder.

Solid-liquid mixtures have been employed to detect the equivalence point, where the liquid and solid have the same dielectric constant. Some authors (1) claim that the detection of the equivalence point is

not sharp enough for accurate measurements. However, others (2,3) feel that it is a good method. There are several disadvantages: firstly, it is time consuming; again, it is experimentally cumbersome, and requires multiple readings on each sample; and finally, contamination of the sample by the liquids employed may occur.

Certain types of experiments require that the dielectric constant of a substance be known from only one measurement, hence the above method is impractical. To fulfill this need many have tried to determine the dielectric constant by means of a capacitance reading on a powdered sample. The difficulty in this type of measurement arises in the attempt to obtain the dielectric constant ε_1 of the material comprising the powder from the observed dielectric constant ε_m. In a suspension the dielectric constant of the suspending medium ε_2 must also be considered.

Many empirical and semi-empirical equations have been put forward to solve this problem. Purely theoretical considerations are impossible and hence simplifications or approximations must be introduced. This paper is involved in testing out these various formulae with the hope of finding one that gives the most accurate value of the true dielectric constant of the solid material.

B General Theory of Dielectric Behavior (4)

The ideas and terms employed in the studies of dielectric materials can best be explained by the use of an example.

Consider a condenser consisting of two parallel plates in a vacuum whose distance apart "d" is small compared with their linear dimensions, and suppose they are electrically charged with the charges + σA and - σA respectively. A is surface area of a plate and + σ is the charge per unit area. The electric field between these plates is given as

$$E = 4 \pi \sigma \qquad [1]$$

where E is practically homogeneous and directed perpendicular to the surface.

Now suppose the space between the plates to be filled with a homogeneous dielectric material while the charge on the plates remains unaltered. This will cause a drop in the electric field to a smaller value, and the ratio of its former value to the present one is denoted by the static dielectric constant ε_s,

Therefore,
$$E = \frac{4 \pi \sigma}{\varepsilon_s} \qquad [2]$$

under the new conditions.

This drop in the field strength accompanying the insertion of the dielectric might also be achieved by reducing the surface density σ of the electric charge by the amount

$$P = \sigma \left(1 - \frac{1}{\varepsilon_s} \right) = \sigma \left(\frac{\varepsilon_s - 1}{\varepsilon_s} \right) \qquad [3]$$

Therefore the influence of the electric field on the dielectric is

equivalent to charging the two surfaces of the dielectric with charges of opposite sign in such a way that the positive condenser plate is faced by the negatively charged surface of the dielectric, and vice-versa. The surface density of the charge is constant and amounts to P. P is called the polarization of the dielectric.

The introduction of the polarization P through the displacement of charges is rather fictitious because these charges cannot be removed from the dielectric. They compensate charges of opposite sign but equal value of the condenser plates. It is customary then to introduce a new field-quantity D, which is described in terms of the true charge. This is the electric displacement, defined by;

$$D = 4 \pi \sigma \qquad [4]$$

In a vacuum, therefore D = E. In dielectrics however;

$$D = \varepsilon_s E \qquad [5]$$

and

$$D = E + 4 \pi P \qquad [6]$$

The surface charges ± PA give rise to an electric dipole moment M of the dielectric given by;

$$M = PA\, d = PV \qquad [7]$$

where d is the distance between the plates and V is the volume of the dielectric. Combining equations 5, 6 and 7,

$$\varepsilon_s - 1 = \frac{4 \pi M}{VE} = \frac{4 \pi P}{E} \qquad [8]$$

C A Summary of the equations employed in deriving the dielectric constants of the components of a mixture or suspension.

Early attempts (5,6,7,8,9,10,11,12) to relate the apparent dielectric constant of the substances comprising the powders or suspensions, assumed additivity of the molar polarization:(13)

$$[P] = \sum_k x_k [P]_k \qquad [9]$$

where x_k are the mole fractions of the components. Using the definition of molar polarization for a powder in a vacuum,

$$[P] = \frac{\varepsilon - 1}{\varepsilon + 2} \frac{M}{d} \qquad [10]$$

where M is the molecular weight and d the density of the material. Hence

$$\frac{\varepsilon - 1}{\varepsilon + 2} = \sum_k \psi_k \frac{\varepsilon_k - 1}{\varepsilon_k + 2} \qquad [11]$$

where ψ_k are the volume fractions of the components. In the case of a crystalline powder in a vacuum

$$\frac{\varepsilon_m - 1}{\varepsilon_m + 2} = \int \frac{\varepsilon_1 - 1}{\varepsilon_1 + 2} \qquad [12]$$

or in a suspension

$$\frac{\varepsilon_m - \varepsilon_2}{\varepsilon_m + 2\varepsilon_2} = \int \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 + 2\varepsilon_2} \qquad [13]$$

Where $\int$ refers to the volume fraction of the solid comprising the powder.

Wiener (14) by assuming a formal arrangement of spheres or cylinders which were not touching proposed the following equations:

In general,

$$\frac{\varepsilon_m - \varepsilon_2}{\varepsilon_m + u} = \mathcal{f} \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 + u} \qquad [14]$$

where for any aggregate u must be between o and ∞. He assumed that u would depend only on the shape and size of the powder particles and not on $\mathcal{f}$.

For spheres

$$\frac{\varepsilon_m - \varepsilon_2}{\varepsilon_m + 2\varepsilon_2} = \mathcal{f} \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 + 2\varepsilon_2} \qquad [15]$$

and for cylinders

$$\frac{\varepsilon_m - \varepsilon_2}{\varepsilon_m + \varepsilon_2} = \mathcal{f} \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 + \varepsilon_2} \qquad [16]$$

The dependence of u only on shape and size was shown to be incorrect by Stöcker's(15) measurements.

Wagner (11) also proposed the following empirical equation

$$\frac{\varepsilon_m - \varepsilon_2}{3\varepsilon_2} = \mathcal{f} \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 + 2\varepsilon_2} \qquad [13a]$$

Wiener's theory was extended by Bruggeman (16) who assumed a random arrangement and obtained for a porphyritic dispersion of randomly orientated laminae of undefined profile, the following equations:

$$\varepsilon_m = \varepsilon_1 \left(\frac{3\varepsilon_2 + 2\int(\varepsilon_1 - \varepsilon_2)}{3\varepsilon_1 - \int(\varepsilon_1 - \varepsilon_2)} \right) \qquad [17]$$

and more specifically for spheres

$$1 - \int = \frac{\varepsilon_1 - \varepsilon_m}{\varepsilon_1 - \varepsilon_2} \sqrt[3]{\varepsilon_2 / \varepsilon_m} \qquad [18]$$

Böttcher (17) made the assumption that the environment of a spherical particle may be considered as a continuous dielectric with a dielectric constant ε_m. Thus he arrives at the equation

$$\frac{\varepsilon_m - \varepsilon_2}{3\varepsilon_m} = \int \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 + 2\varepsilon_m} \qquad [19]$$

Guillien (18) proved that the dielectric constant ε_m of a dispersion of a material of dielectric constant ε_1, depends not only on ε_1, ε_2 and $\int$ but also on the form of the particles, and is independent of the size of the particles. The minimum dielectric constant was found for spherical particles, while a considerable increase was found for non-spherical particles.

Voet (19) extended Bruggeman's equation by introducing a form factor f for non-spherical particles.

$$1 - fd = \frac{\varepsilon_1 - \varepsilon_m}{\varepsilon_1 - \varepsilon_2} \sqrt{\varepsilon_2 / \varepsilon_m} \qquad [20]$$

f = 1 for spherical powders and > 1 for non-spherical powders. The concept works fairly well in dilute dispersions but an agglomeration factor must be introduced when the particles are touching.

Polder and Van Santen (20) extended Bottcher's formula. They assume that the mixtures that they speak about are always as homogeneous as possible. If one fixes one's attention on one special particle in the mixture one can hypothesize that the mean value of the field in the interior of the particle, under these simplified conditions, provides a good approximation for the actual mean field in the special particle. In general they derive the equation

$$\varepsilon_m = \varepsilon_2 \left[1 - \frac{1}{3} \sum \left\{ f_i (\varepsilon_i - \varepsilon_2) \sum_{i=1}^{3} \frac{1}{\varepsilon_m + (\varepsilon_i - \varepsilon_m) A_i} \right\} \right]^{-1} \qquad [21]$$

where A_i is determined by the shape of the particles and is the depolarization factor of an ellipsoid.

For spherical particles they propose the following equation,

$$\varepsilon_m = \varepsilon_2 \left[1 + 3f \left(\frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 - 2\varepsilon_2} \right) \right] \qquad [22]$$

for small values of f.

When considering needle-like particles if $\varepsilon_2 >> \varepsilon_1$ then

$$\varepsilon_m = \varepsilon_2 \left(1 - \frac{5}{3} f\right) \qquad [23]$$

and if $\varepsilon_1 >> \varepsilon_2$ then

$$\varepsilon_m = \varepsilon_2 + \frac{f}{3} \varepsilon_1 \qquad [23a]$$

They also develop similar limiting equations for disc like particles; if $\varepsilon_2/\varepsilon_1 \ll 1$

$$\varepsilon_m = \varepsilon_2 + \frac{2}{3} f \varepsilon_1 \qquad [24]$$

and if $\varepsilon_1/\varepsilon_2 \ll 1$

$$\varepsilon_m = \varepsilon_2 \left[1 - \frac{f}{3} \left(2 + \frac{\varepsilon_2}{\varepsilon_1} \right) \right] \qquad [25]$$

Byvoet (21) extended Bruggeman's equation by developing an expression for the constant μ, hence they obtained.

$$\frac{\varepsilon_m - \varepsilon_2}{\varepsilon_m + \mu} = f \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 + \mu} \qquad [26]$$

where

$$\mu = 2 \sqrt{\varepsilon_1 \varepsilon_2} \left[\frac{1}{2} \left(\frac{\varepsilon_1}{\varepsilon_2} \right)^{1/3} + \frac{1}{2} \left(\frac{\varepsilon_1}{\varepsilon_2} \right)^{2/3} \right]^{f/2} \qquad [27]$$

Pearce (22) noted by experiment that the following relationship holds,

$$\frac{\varepsilon_m - \varepsilon_2}{\varepsilon_1 - \varepsilon_2} = \frac{(1 - v) f}{1 - v f} \qquad [28]$$

where v is a constant for a given material.

Higuchi (23a), by assuming that the powder is comprised of uniform isotropic spheres and that the particles see a uniform field around it such that

$$\bar{\varepsilon}_o = v_1 \bar{\varepsilon}_1 + v_2 \bar{\varepsilon}_2$$

where $\bar{\varepsilon}_1$ and $\bar{\varepsilon}_2$ are the average field vectors in the continuous phase. He also takes particle - particle interactions into account. He relates his theory to that of Pearce's by

$$v = \frac{\left(\frac{\varepsilon_1}{\varepsilon_2} - 1\right)\left(\frac{\varepsilon_1}{\varepsilon_2} + 2\right) - K\left(\frac{\varepsilon_1}{\varepsilon_2} - 1\right)^2}{\left(\frac{\varepsilon_1}{\varepsilon_2} + 2\right)^2 - K\left(\frac{\varepsilon_1}{\varepsilon_2} - 1\right)^2} \qquad [29]$$

and in general

$$\varepsilon_m = \frac{2\varepsilon_2^2(1-\phi) + \varepsilon_2\varepsilon_1(1+2\phi) - K\varepsilon_2\left(\frac{\varepsilon_1 - \varepsilon_2}{2\varepsilon_2 + \varepsilon_1}\right)^2 (2\varepsilon_2 + \varepsilon_1)(1-\phi)}{\varepsilon_2(2+\phi) + \varepsilon_1(1-\phi) - K\left(\frac{\varepsilon_1 - \varepsilon_2}{2\varepsilon_2 + \varepsilon_1}\right)^2 (2\varepsilon_2 + \varepsilon_1)(1-\phi)} \qquad [30]$$

where K is an empirical factor. Precise knowledge of K would require, among other factors, details of the radial distribution function for random spheres as a function of ϕ. The author states that K depends on the asphericity of the sample and on particle - particle interactions that lead to apparent ashericity effects.

Hough and Reynolds (23) have shown that all the equations relating to mixtures could be simplified to the following two equations, namely,

$$\varepsilon_m = \varepsilon_2 + (\varepsilon_1 - \varepsilon_2)\phi f_1 \qquad [31]$$

for dispersed particles in a continuous medium, and

$$(\varepsilon_m - \varepsilon_1)\phi_1 f_1 + (\varepsilon_m + \varepsilon_2)\phi_2 f_2 = 0 \qquad [32]$$

where the particle size of the two components is of the same order of magnitude. f_1 and f_2 are field ratios and unfortunately it is only possible to calculate them exactly for the case of parallel slabs or the case of infinitely diluted dispersions of particles of ellipsoidal shape; in all other cases it is necessary to make an approximate calculation. Most of the published formulae differ from one another in the approximation considered appropriate.

Pradham and Gupta (32) used equation (31) and determined f_1 obtaining the following equations;

for spheres

$$2\,\varepsilon_m^2 + \varepsilon_m \left[\varepsilon_1\,(1-3f) - \varepsilon_2\,(2-3f)\right] - \varepsilon_1\varepsilon_2 = 0 \qquad [33]$$

for lamellae

$$\varepsilon_m \left[3\varepsilon_1 - f(\varepsilon_1 - \varepsilon_2)\right] - 2f\varepsilon_1^2 - \varepsilon_1\varepsilon_2\,(3-2f) = 0 \qquad [34]$$

and for rods

$$3\varepsilon_m^2 + \varepsilon_m\,(\varepsilon_1 - \varepsilon_2)\,(3-5f) - \varepsilon_1\,\varepsilon_2\,(3-f) - f\varepsilon_1^2 = 0 \qquad [35]$$

Brown (24) also assumes an average electric field that every particle experiences. By assuming that the microscopic structure of the mixture possesses no long-range order his calculation follows that of a calculation in molecular theory carried out by Yvon (25). By doing so he arrives at the following equations;

For a uniform electric field,

$$\frac{\varepsilon_m}{\varepsilon^1} = 1 - \frac{1}{3} pg\left(\frac{\Delta^1}{\varepsilon_1}\right)^2 + \left[- \frac{2}{9} pg\,(p - g) + \text{---------} \right] \qquad [36]$$

For a uniform displacement victor

$$\frac{\varepsilon}{\varepsilon^{11}} = 1 + \frac{2}{3} pg\left(\frac{\varepsilon^{11}}{\Delta^{11}}\right)^2 + \frac{5}{9} pg\,(p - g) + \text{---------} \qquad [37]$$

for an array of parallel plates

$$n = n^1 + \frac{1}{6} pg\,\Delta^2 - \frac{1}{18} pg\,(p - g) + \text{----------} \qquad [38]$$

the dashed lines indicate that further terms can be added which involve statistical expressions that are difficult if not impossible to evaluate.

In the above equations,

$\varepsilon^1 = p\,\varepsilon_1 + g\,\varepsilon_2$ where p = volume fraction

$g = 1 - p$

$$\Delta^1 = \varepsilon_1 - \varepsilon_2$$
$$(\varepsilon^{11})^{-1} = p\,\varepsilon_1^{-1} + g\,\varepsilon_2^{-1}$$
$$\Delta^{11} = \varepsilon_1^{-1} - \varepsilon_2^{-1}$$

$n = \ln \varepsilon_m$, $n_A = \ln \varepsilon_1$, $n_B = \ln \varepsilon_2$, $n^1 = p\,n_A + g n_B$ and

$\Delta = n_A - n_B$

Kamiyoshi (26,27) has derived an empirical and a theoretical equation that seems to fit the experimental data in the range of volume fraction 0.4 - 0.6. He has modified Rayleigh's (28) equation with the help of Lunge's (29) considerations to develop his theoretical equation.

He considers the case where the volume fraction is 0.5 and views the system as a formal array of condensers of the same capacity, connected in parallel series, each being filled with either the suspending medium or the solid material to be measured. The equations derived are the following:

empirically

$$\varepsilon_m - \varepsilon_2 = (ap - b)\ (\varepsilon_1 - \varepsilon_2) \qquad [39]$$

$$a = 0.900$$

$$b = 0.139$$

and more rigorously

$$\varepsilon_m = \frac{2\ E_1\ E_2}{E_1 + E_2} \qquad [40]$$

where

$$E_1 = \varepsilon_2 \left(1 + \frac{3\phi}{\frac{\varepsilon_1 + 2\varepsilon_2}{\varepsilon_1 - \varepsilon_2} - \phi - 0.523\phi^{10/3}\ \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 + \frac{4}{3}\varepsilon_2}} \right) \qquad [41]$$

where ε_2 = dielectric constant of the medium

ε_1 = dielectric constant of the spheres

$$E_2 = \varepsilon_1 \left(1 - \frac{3\ (1 - \phi)}{\frac{2\varepsilon_1 + \varepsilon_2}{\varepsilon_1 - \varepsilon_2} + (1 - \phi) - 0.523\ (1 - \phi)^{10/3}\ \frac{\varepsilon_1 - \varepsilon_2}{\frac{4}{3}\ \varepsilon_1 + \varepsilon_2}} \right) [41]$$

CHAPTER II

Experimental Methods and Materials

A General

The assembly of the apparatus is that shown in Figure 1. The requirements of the sample cell were the most demanding since a rigid electrical assembly was required in order to obtain a constant capacitance reading for an empty cell over a long period of time. A cell which was easily filled and emptied with different samples had to be designed. It had to be vacuum tight since the standard dielectric liquids had to be vacuum distilled into it. The vacuum distillation was necessary in order to prevent air bubbles from becoming trapped in the powder bed. Since the dielectric constant is a function of temperature, a system of thermostating the cells had to be devised. This was done by a series of inter-connected water jackets which were in turn connected to a large water bath which was thermostated at 25 ±.1°C. An allowance also had to be made for a solvent purification prior to the vacuum distillation into the cells. This was accomplished by performing a trap to trap vacuum distillation from a flask at room temperature to one at liquid air temperatures. The absence of water in the standard dielectric liquids was assured by stirring the solvents overnight in sodium sulphate prior to the purifying vacuum distillation. Additional precautions were taken in this regard by adding a small quantity of sodium sulphate to the flask which was to store the purified solvent. Capacitance measurements had to be made on all six cells with maximum reproducibility. This was accomplished by fixing a permanent coaxial

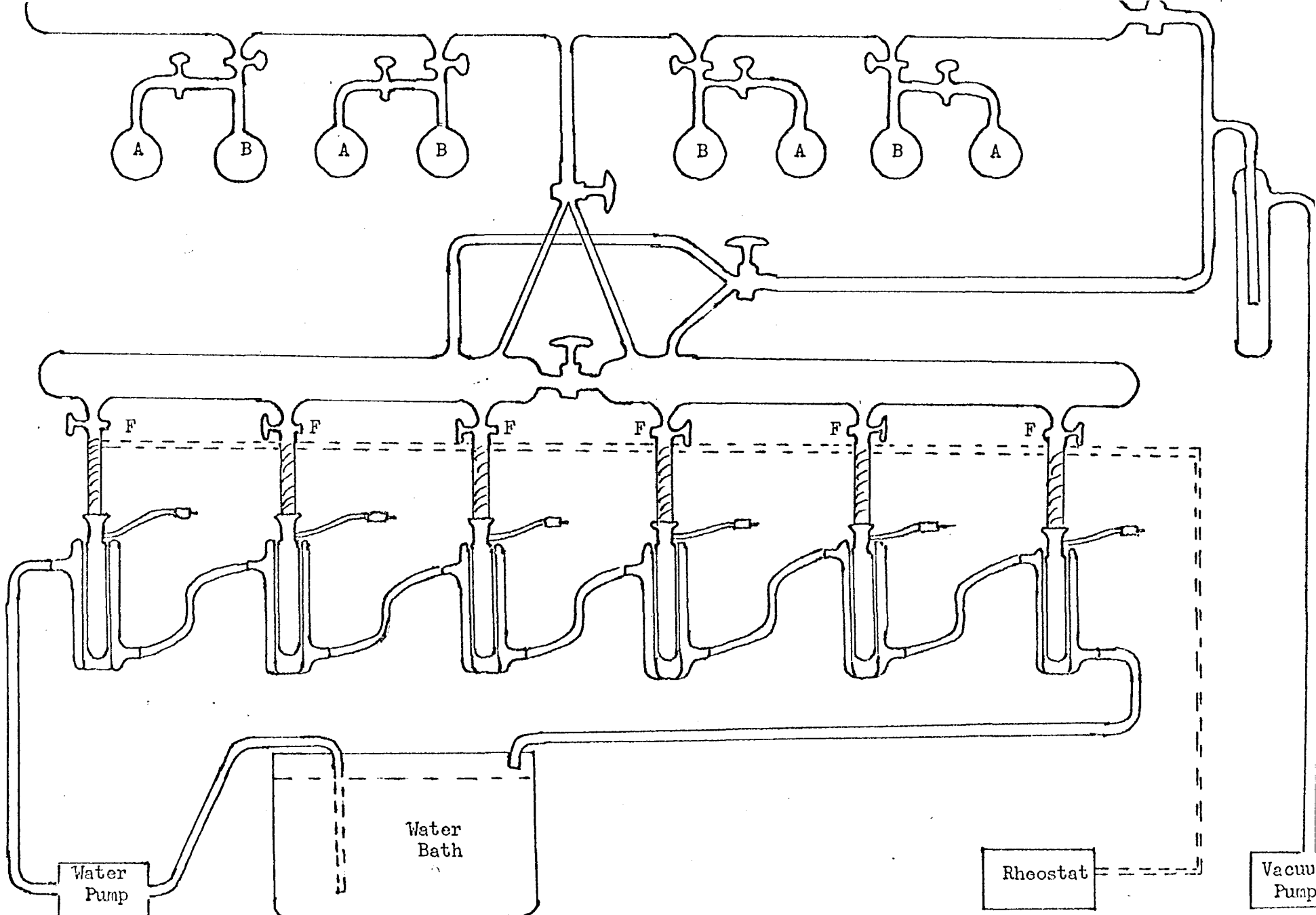


Figure 1.

cable lead to all the cells which in turn was connected to a longer coaxial cable that lead to the oscillometer.

B Cell for Measurement of Dielectric Constant

The cell design is that shown in Figure 2. It consists of three concentric glass cylinders. Mercury serves as the condenser plates by filling the space between the first two cylinders and by filling the inner cylinder, forming a cylindrical condenser. End effects were minimized by making the outside mercury cylinder extend both above and below the centre column of mercury by approximately 2 centimeters. The wire leads were fixed firmly into the cell by employing epoxy resin. The leads were first placed into the mercury, then the epoxy resin was forced into the cylinders so that it rested on the mercury surface forming a seal between the mercury and the lead wire and between the mercury and the walls of the glass cylinders. The aspect of the cell design is the most important since a change in the level of the mercury in either plate causes a large difference in the capacitance of the cylindrical condenser thus achieved. In earlier designs it was found that the mercury soon became contaminated and wetted the glass walls, thus altering the dimensions of the condenser. The leads to the cell were shielded coaxial cables in two sections. The first lead was a short one of approximately 25 centimeters. A lead any longer than this would make the changing of samples cumbersome. The second lead was approximately a meter in length and provided the connection between the cell and the oscillometer which was located at a lower level. The connectors between the first and second leads were Armaco shielded phono plugs # TFP 303 and between the second lead and the oscillometer were

Sample Cell

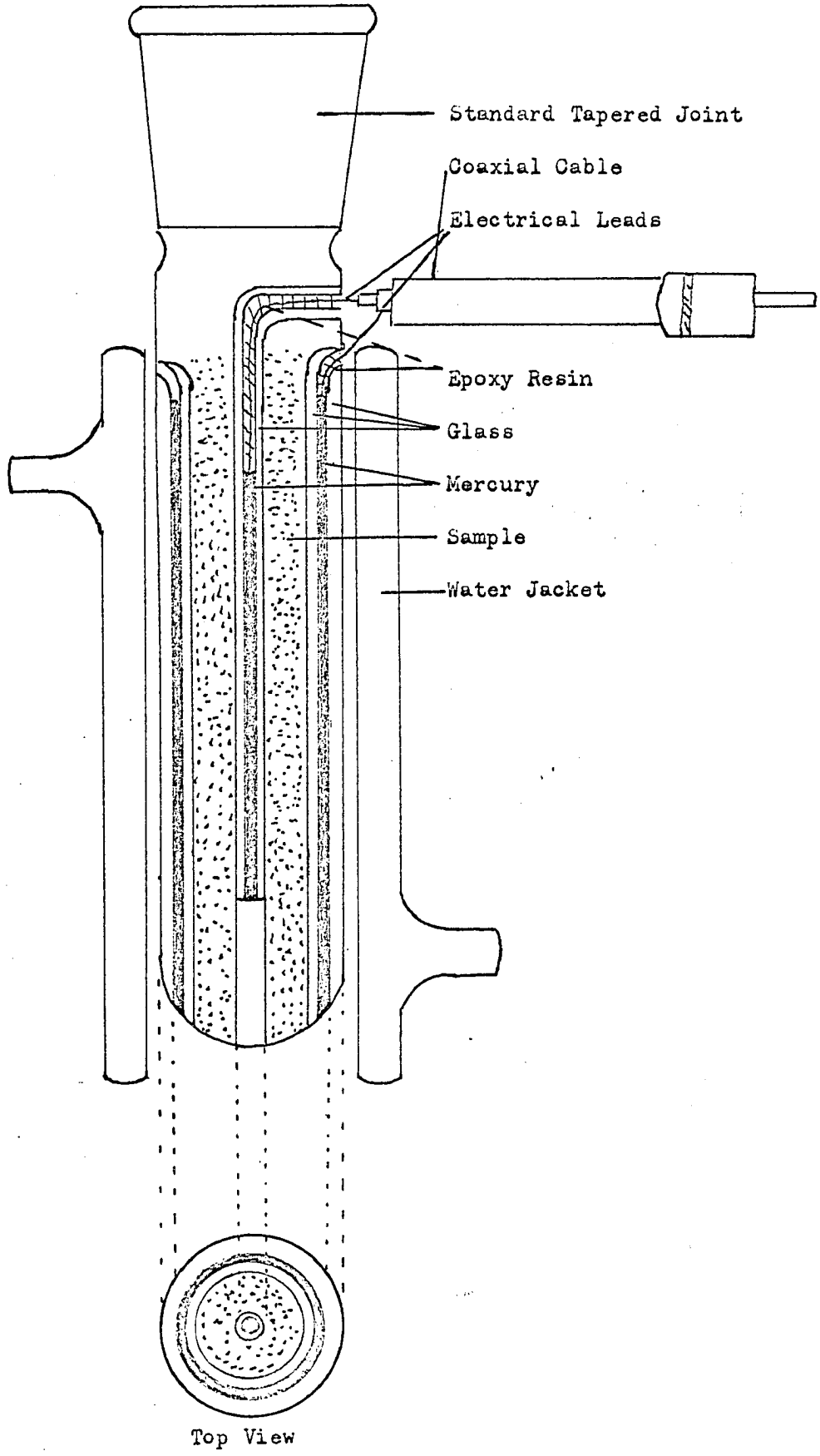


Figure 2.

Water Jacket

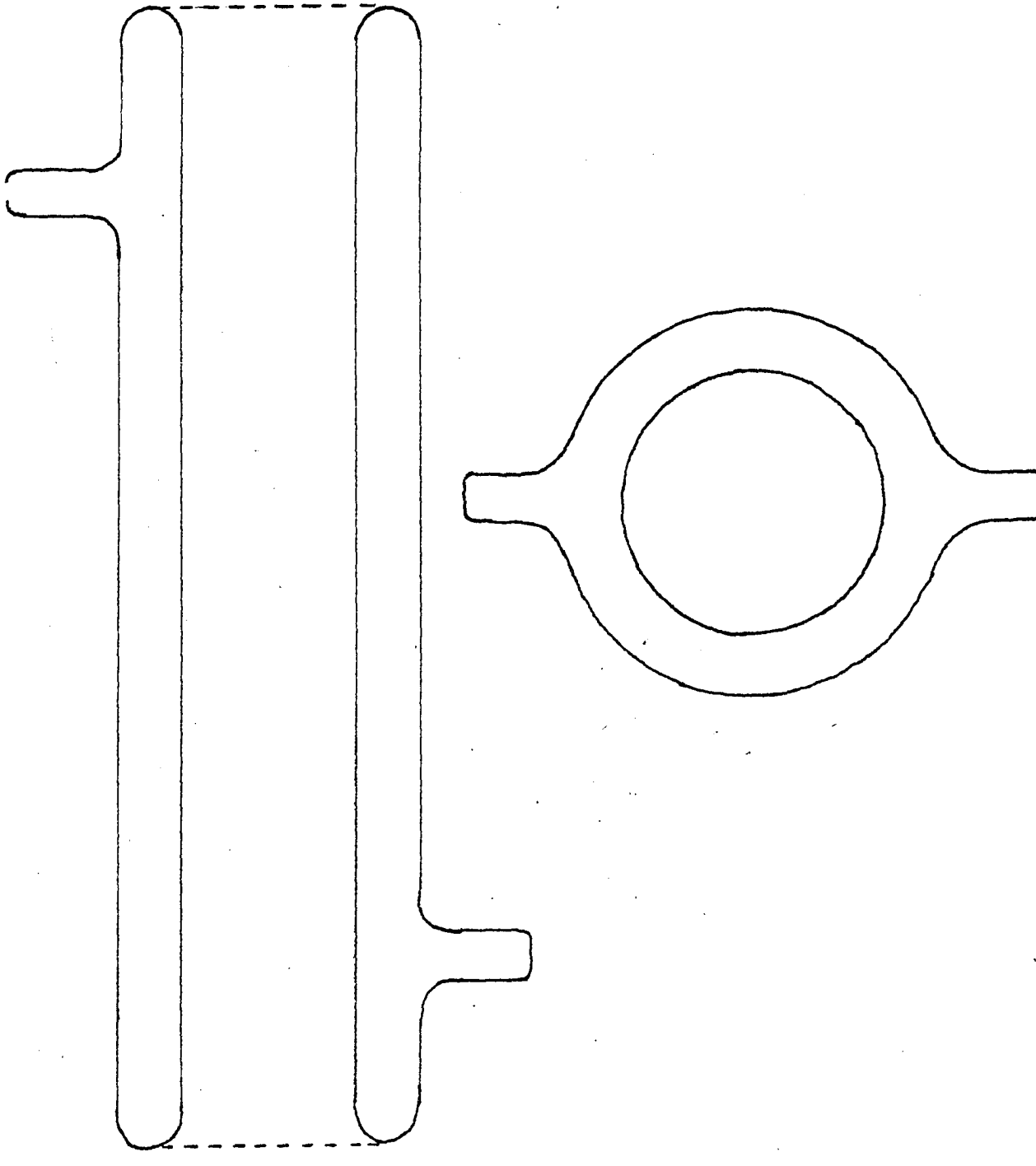


Figure 3.

Amphenol 83-1 SP connectors. It was found that manipulation of the connectors introduced an error of ± 50 arbitrary capacitance units in the case of the former, but of only ± 10 units in the case of the latter. Accordingly once the cell was in place, the connection between the first and second lead was not disturbed for a series of readings on a particular sample. All connections were made at the end of the second lead by means of the amphonol connector, limiting this type of error to ± 10 units on readings of about 10,000.

C Temperature Control System

The cells were thermostated by means of the water jacket shown in figures 2 and 3. Water at 25°C was pumped through the jackets from a large bath. The bath temperature was controlled by a relay actuated by a mercury thermoregulator. Variations in the temperature of the bath were always within a range of 0.1°C. Since periods of heating and cooling were approximately 30 seconds duration, and since the heat capacity of the cell assembly was large, the variations of the temperature of the pure liquids or mixtures were presumably within a much smaller range. A period of approximately one half-hour was allowed for the cells to reach thermal equilibrium from 0°C to 25°C.

D Vacuum System

The entire system was composed of two major sections. The first section was employed for the purification and storing of the standard dielectric liquids. The second section held the cells where the capacitance readings were taken. The entire system with the exception of flasks A (figure 1) was evacuated. The standard dielectric liquids

were then placed in the flasks A. They were frozen at liquid air temperatures, followed by a period of pumping to remove any air. This procedure was repeated several times until all the dissolved air in the solvents was removed. A vacuum distillation from the flasks A at room temperature to flasks B at liquid air temperatures was then carried out. Only the first 100 ml fraction was employed. These purified solvents were then vacuum distilled into the test cells which were kept at 0°C by means of ice-water baths. The flasks B were at room temperature for this distillation.

The glass tubing between the cells and the stopcocks F was heated by means of resistance wire to prevent condensation of solvent on the unthermostated walls. This phenomenon was objectionable because it was accompanied by "bumping" (i.e. boiling) in the test cell.

E Capacitance Measurements

A commercial instrument (the Sargent Oscillometer Model $\overline{V}$ - S - 29180) was used for measuring capacitance. It employs a resonant circuit method at a frequency of approximately 5 megacycles. The results are obtained in arbitrary capacitance units. The sensitivity of a typical reading was ± 20 units for a reading of 10,000 to 15,000 units.

F Volume Calculations for the Cells

The cell volume was calibrated by means of a 10 ml burette and a cathetometer. The cathetometer was used to measure the distance from the top of the ground glass joint to the bottom of the meniscus of the known volume of water in the cell. This was repeated for a number of different volumes and a volume versus difference in Cathetometer reading graph was set up. (Table I and Figure 4). Thus by taking a cathetometer reading on a cell filled with the powder, it is possible to determine the volume occupied by the powder from the graph.

TABLE I

Volume occupied by liquid (ml)	Cathetometer reading difference (cm)
12.96	5.835
13.03	5.795
13.11	5.675
13.20	5.600
13.30	5.535
13.38	5.445
13.50	5.355
13.60	5.245
13.70	5.145
13.80	5.030
14.00	5.000

Determination of the Volume Occupied by a Sample

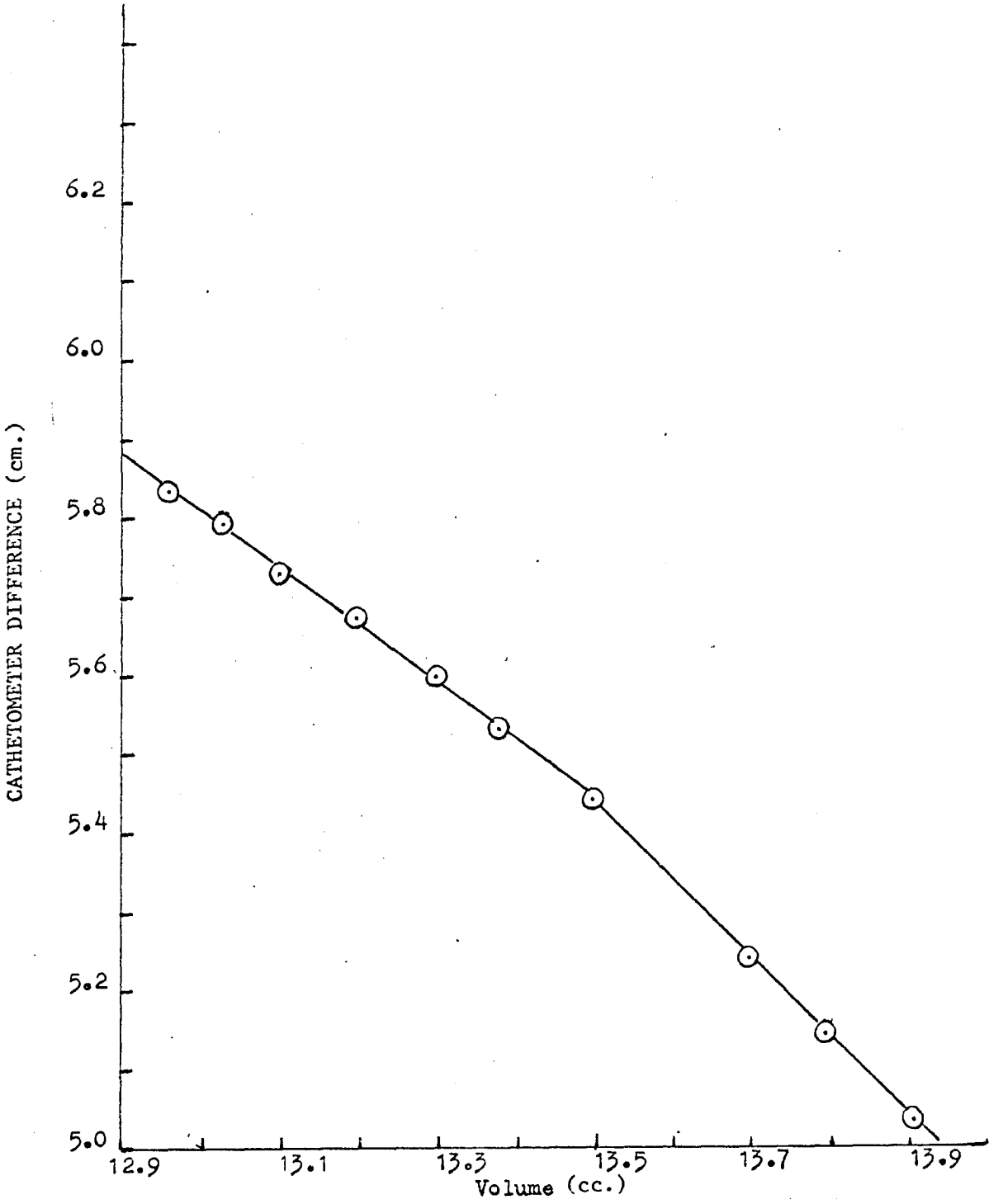


Figure 5.

G Density Measurements

It was reported by the Minnesota Mining Company that the glass beads used in this study were not all of the same density, the smaller beads having lower values. To determine volume fractions the density had to be known accurately. It was impossible to determine the density of the beads by conventional procedures since gas bubbles were formed between the beads in a heterogeneous mixture of the liquid and beads. Hence the density had to be determined by the use of a vacuum distillation. Two burettes were set up in the manner shown in figure 4. A known weight of beads is added to the burette A. The volume V_1 of liquid is noted in burette B. A vacuum distillation is carried out and the volume V_2 and V_3 are observed. The volume occupied by the beads was thus obtained and the density of the beads calculated. The values ranged from 2.54 for the larger beads to 2.35 gm/cc for the smallest beads.

H Materials

The glass beads used were 3M "Superbrite" glass beads manufactured by the Minnesota Mining and Manufacturing Company. The ground glass samples were of the type 7900 and were obtained from the Corning Glass Company. The chloroform, reagent grade number C-200, ethyl acetate, reagent grade number E-145, methyl acetate, reagent grade number M-203, and 1,2 - dichloro-ethane reagent grade number E-175 were obtained from the Fisher Scientific Company. Anhydrous Titanium Oxide (Fisher certified reagent T-315), Calcium Carbonate (Merck reagent. 72 29 1-precipitated) Lead Oxide, Mono (Fisher N.F. - L-68), Barium Sulphate (Fisher certified B 68), Silicon Dioxide (Silica) (Fisher reagent - S -152) and Sulphur (Fisher V.S.P - S - 593). The compressed Silica was made of Cab-O-Sil M-5 manufactured by the Cabot Corporation.

Volume Measuring Apparatus

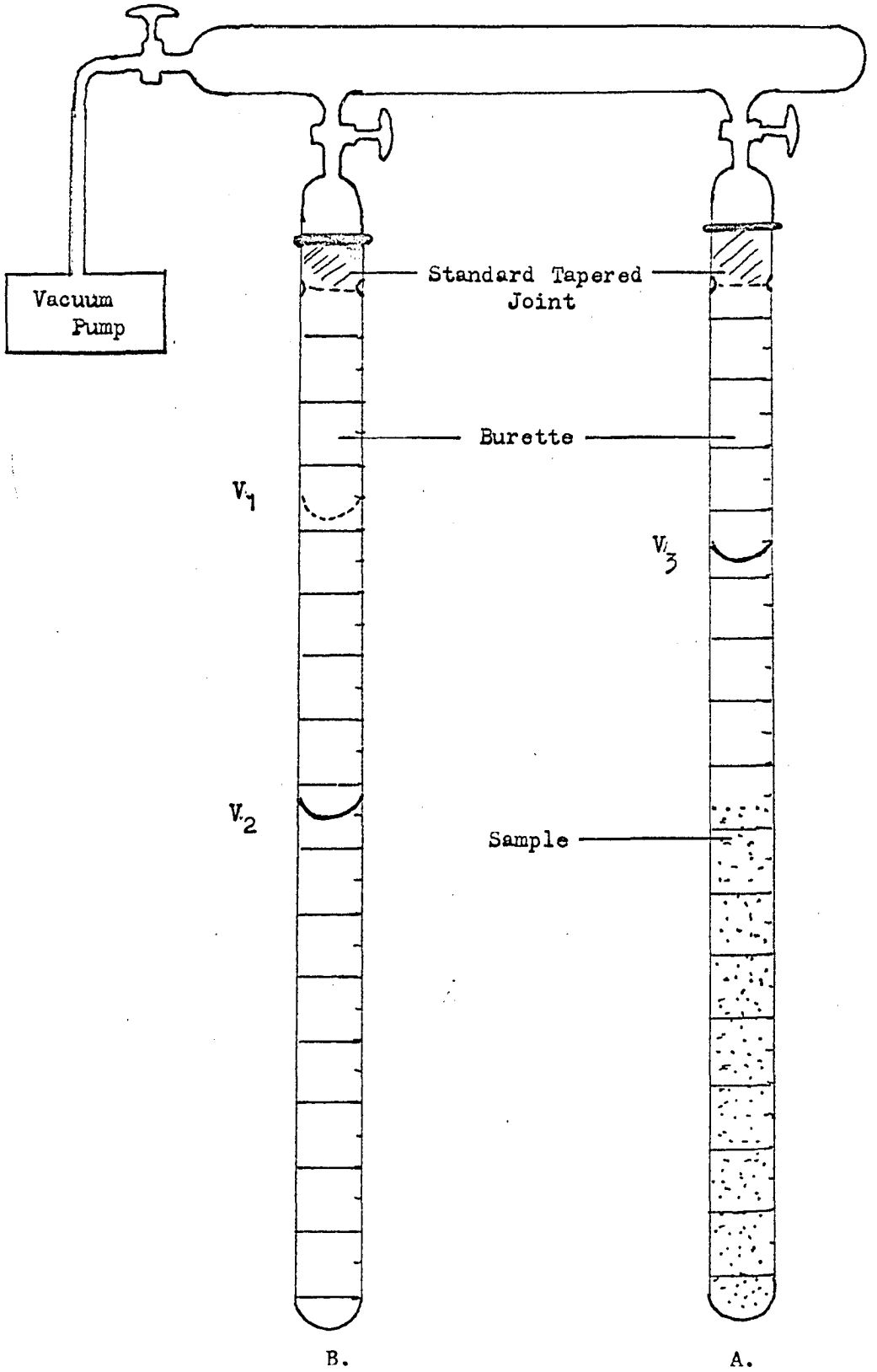
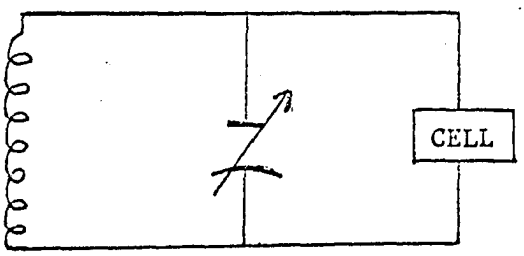


Figure 4.

I Calculation of Dielectric Constants

The relations of capacitance, resistance and dielectric constant are determined by the characteristics of the cell which, together with its parallel calibrated measuring capacitances, is arranged in the resonant circuit as shown in simple form in the figure below



Sincethe cell capacitance and the measuring capacitances are in parallel, the net capacitance is the sum of the two and therefore an increase in the cell capacitance may be measured by removing from the calibrated capacitance an exactly equivalent amount. The effect of having removed this equivalent amount is indicated in the instrument by the resulting re-establishment of the original frequency.

The cell configuration is essentially equivalent to a single cylindrical condenser except that in this case the two metallic plates (Mercury) are separated by three units of dielectric material, these being the two thicknesses of glass from which the cell is made and the sample liquid or powder when filled or vacuum when empty. Accordingly, the total capacitance of the cell is that of several capacitances in series. Since in a given cell the two glass walls are constant in thickness and property, the total capacitance may be considered as that of one variable and one constant capacitance which are termed respectively C_s and C_g. These two being in series, the total cell capacitance C is then,

$$C = \frac{C_g C_s}{C_g + C_s} \qquad (1)$$

As a special case of C_s when the dielectric constant is 1, the empty evacuated cell may be referred to as Co whence,

$$C_s = C_o K \qquad (2)$$

where K is the dielectric constant of the sample. Hence, the total capacitance in terms of the dielectric constant of a contained sample material is, neglecting fringe effects,

$$C = \frac{C_g C_o K}{C_g + C_o K} \qquad (3)$$

The instrument scale is in equal arbitrary units of capacitance and the point of reference is established by adjusting to resonance when the cell is empty. The capacitance in effect when the scale reading S is zero is

$$C = \frac{C_g C_o}{C_g + C_o} \qquad (4)$$

On subsequent addition of a test sample having a dielectric constant of K, resonance will be re-established by adjustment of the calibrated capacitors to produce a scale reading of S units indicating a change in the capacitance of the sample cell equal to the difference between equations 3 and 4 or,

$$S = \frac{C_g C_o K}{C_g + C_o K} - \frac{C_g C_o}{C_g + C_o} \qquad (5)$$

where C_g and C_o are expressed in scale units. This relation may be

expressed in terms of the dielectric constant K by rearrangement as follows:

$$K = \frac{C_g + S\left(Cg/Co + 1\right)}{C_g - S\left(\frac{Co}{Cg} + 1\right)} \qquad (6)$$

For the measurement of dielectric constants, the cell constant Cg and the ratio of constants Cg/Co must be determined for use in equation (6). These constants may be derived by measurement of two standard dielectric liquids, employing equations derived from the fundamental equation (5) as follows,

$$S_1 = \frac{C_o C_g K_1}{C_o K_1 + C_g} - \frac{C_o C_g}{C_o + C_g} \qquad (7)$$

$$S_2 = \frac{C_o C_g K_2}{C_o K_2 + C_g} - \frac{C_o C_g}{C_o C_g} \qquad (8)$$

Where K_1 and K_2 are the dielectric constants of the standard liquids, S_1 and S_2 the corresponding scale readings. By rearrangement of the quotient of 7 and 8.

$$\frac{Co}{Cg} = \frac{S_2 (K_1 - 1) - S_1 (K_2 - 1)}{K_1 S_1 (K_2 - 1) - K_2 S_2 (K_1 - 1)} \qquad (9)$$

if $\frac{Co}{Cg} = x$

Then

$$S_2 (K_1 - 1) - S_1 (K_2 - 1) = K_1 S_1 x (K_2 - 1) - K_2 S_2 (K_1 - 1) x$$

$$S_2 (K_1 - 1) [1 + K_2 x] = S_1 (K_2 - 1) [K_1 x + 1]$$

$$\frac{(K_2 - 1)}{S_2} = \left(\frac{K_1 - 1}{S_1}\right)\left(\frac{1 + K_2 x}{K_1 x + 1}\right)$$

$$= \left(\frac{K_1 - 1}{S_1 (K_1 x + 1)}\right) + \left(\frac{K_1 - 1}{S_1 (K_1 x + 1)}\right) K_2 x \qquad (10)$$

hence if a plot of $(K_2 - 1)/S_2$ vs K_2 is made one should obtain a straight line and if the slope is divided by the intercept one obtains a value of C_o/C_g.

The value may then be substituted in the following rearrangement of equation (6) to determine the value of Cg.

$$Cg = \frac{S\left(\frac{Cg}{Co} + 1\right) + KS\left(\frac{Co}{Cg} + 1\right)}{K - 1} \qquad (11)$$

Knowing the values of the cell constants Co and Cg one is now able to obtain the dielectric constant of any material by employing equation (6).

J. Calibration of Cells

The cells were calibrated using the following standard dielectric liquids:

	Dielectric Constant	Temperature
Chloroform	4.80	25°C
Ethyl Acetate	6.02	25°C
Methyl Acetate	6.68	25°C
1 - 2 Dichloro Ethane	10.36	25°C

The values given above are those obtained from National Bureau of Standards circular 514.

Table II gives the cell constants for the cells employed.

TABLE II

CELL CONSTANTS

Cell # 1

Standard Dielectric Liquid	Capacitance Reading	
Zero Reading	10932	
Chloroform	14617	$Co/Cg = .18777$
Ethyl Acetate	15250	
Methyl Acetate	15632	$Cg = 11683$
Dichloro Ethane	16792	

Cell # 2

Standard Dielectric Liquid	Capacitance Reading	
Zero Reading	10752	
Chloroform	14604	$Co/Cg = .18342$
Ethyl Acetate	15266	
Methyl Acetate	15645	$Cg = 12294$
Dichloro Ethane	16896	

Cell # 4

Standard Dielectric Liquid	Capacitance Reading	
Zero Reading	11152	
Chloroform	15072	$Co/Cg = .17138$
Ethyl Acetate	15724	
Methyl Acetate	16133	$Cg = 12787$
Dichloro Ethane	17462	

Cell # 5

Standard Dielectric Liquid	Capacitance Reading	
Zero Reading	11115	
Chloroform	14920	$Co/_{Cg}$ = .20630
Ethyl Acetate	15538	
Methyl Acetate	15904	Cg = 11646
Dichloro Ethane	17052	

Cell # 6

Standard Dielectric Liquid	Capacitance Reading	
Zero Reading	11227	
Chloroform	14982	$Co/_{Cg}$ = .17598
Ethyl Acetate	15625	
Methyl Acetate	15974	Cg = 12133
Dichloro Ethane	17248	

N.B. The reported capacitance readings are accurate to ±20 units.

K. Measurement of the Dielectric Constant of a Solid comprising a powder by the use of mixtures with different standard dielectric liquids.

If $\frac{K - 1}{S}$ is plotted against K for a series of standard liquids one obtains a linear plot as indicated in Figure 6. Now if one carries out the same plot for a series of mixtures of the powder with the same dielectric liquids one obtains again a linear plot (fig 6.). The value K in the second plot is taken to be the known dielectric constant of the liquid forming the second component of the mixture. The intersection of these two plots gives the value of the dielectric constant of the solid comprising the powder since at this point the dielectric constant of the liquid is the same as that of the solid.

In actual practice the intersection point was found mathematically by using the slopes and the intercepts for the lines of best fit through the points. The values thus determined are given in Table III.

Determination of the Dielectric Constant of Glass

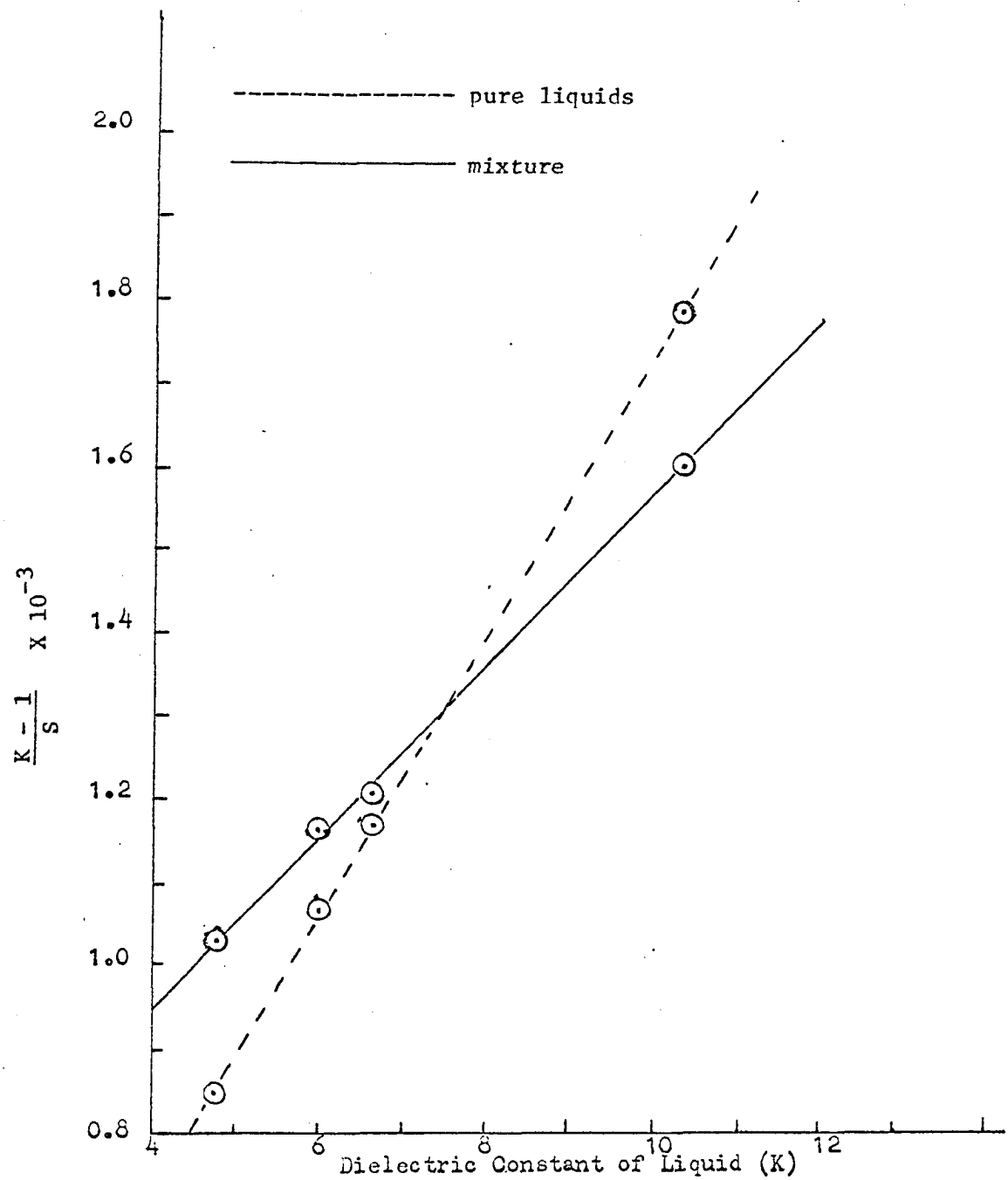


Figure 6.

CHAPTER III

Results:

The experimental results obtained by the intersection of the $(K - 1)/_S$ vs K plots are given in Table III. ε_1 values calculated for glass beads, ground glass, sodium sulphate and calcum carbonate using equations 39, 13, 16, 17, 18, 19, 33, 34, 35, 13a, 37, 38, 22, 40, 30 and 26 are found tabulated in the appendix.

TABLE III

Dielectric Constants determined by the Method of Mixtures.

A - Glass Beads

Size (diameter in cm)	Dielectric Constant
0.03810	7.51
0.04699	7.45
0.02032	7.58
0.01473	7.46
0.01143	7.63
0.00991	7.46
0.00838	7.47
0.00660	7.50
0.00508	7.46
0.00381	7.54
Average	7.50

B - Other Materials

Material	Dielectric Constant
1:1 Mixture of Glass Beads. sizes - .00279 cm .04699 cm	7.32
Ca CO_3 powder	9.33
Ground Glass - 16 mesh	3.56
Ground Glass - 60 mesh	3.49
Ba SO_4 powder	≈ 11.00

CHAPTER IV

Discussion and Conclusions

As expected it is found that the smaller the difference between ε_1 and ε_2 the better does the calculated value of ε_1 fit the experimental data for all equations. This is so since all the equations attempt to account for the non-homogeneity of the dielectric. The smaller this is the less the correction required and the better the fit.

The case where the continuous medium is a vacuum has the most practical value. This is the usual application of the formulae since it is the most convenient measurement to make and it does not disturb the material or introduce a solvent or suspension effect. It was found for the materials and the volume fractions tested, that Bruggeman's equation best fits the experimental data. This is in agreement with results of previous authors (22, 31). If $1 < \varepsilon_1/\varepsilon_2 < 5$ the agreement is much better and is shown in tables XX $\varepsilon_1/\varepsilon_2 = 1.45$, XXI $\varepsilon_1/\varepsilon_2 = 1.25$, and XXII $\varepsilon_1/\varepsilon_2 = 1.12$. The results obtained for methyl acetate as the standard liquid give the most accurate values for the glass beads since $\varepsilon_1/\varepsilon_2$ is closest to unity in this case.

Pearce (22) noted this type of behavior and developed an empirical equation [28] to fit the experimental results for different values of $\varepsilon_1/\varepsilon_2$ by defining an empirical constant v. Higuchi (23a) attempted to redefine this constant by mathematical means by developing the expression [29]. In this expression K is a function depending on particle shape, spatial distribution and volume fraction. Higuchi shows that if

Pearce's empirical equation is valid, K should be independent of volume fraction. Higuchi arbitrarily chooses the data for $PbCl_2$-vacuum which requires a value of K = 0.78 and shows rough agreement between calculated and experimental values of v for other systems in Pearce's equation [28]. However if Pearce's "v" values are used to calculate K, a wide fluctuation is obtained (i.e. Table XXIV in appendix)

The system of glass beads used in this experiment fit in well with Higuchi's assumptions and lends itself to an examination of the validity of the predictions made by Higuchi. The theory is developed for uniform isotropic spheres and this condition is well filled by the samples of glass beads of a particular size. Higuchi predicts that according to the model leading to his equation and estimated higher order effects the expected experimental value of the constant K for uniform true spheres in close packed arrangements should lie in the vicinity of K = 0.3 to 0.4. This is exactly what was found by experiment as is shown in tables IV through XXIII. If K = .35 the experimental values agree well with calculated ones.

The choice of the value of K appears to be critical for $\varepsilon_1/\varepsilon_2 > 5$. For $1 < \varepsilon_1/\varepsilon_2 < 2$ the choice of a value for K is arbitrary for glass beads. This is shown in tables IV through XIII for the values for the dielectric constant of the glass beads in chloroform, ethyl acetate and methyl acetate.

For values of $\varepsilon_1/\varepsilon_2 > 1$ a change in the value of K produces some change but it is not as drastic as those produced when $\varepsilon_1/\varepsilon_2 > 5$.

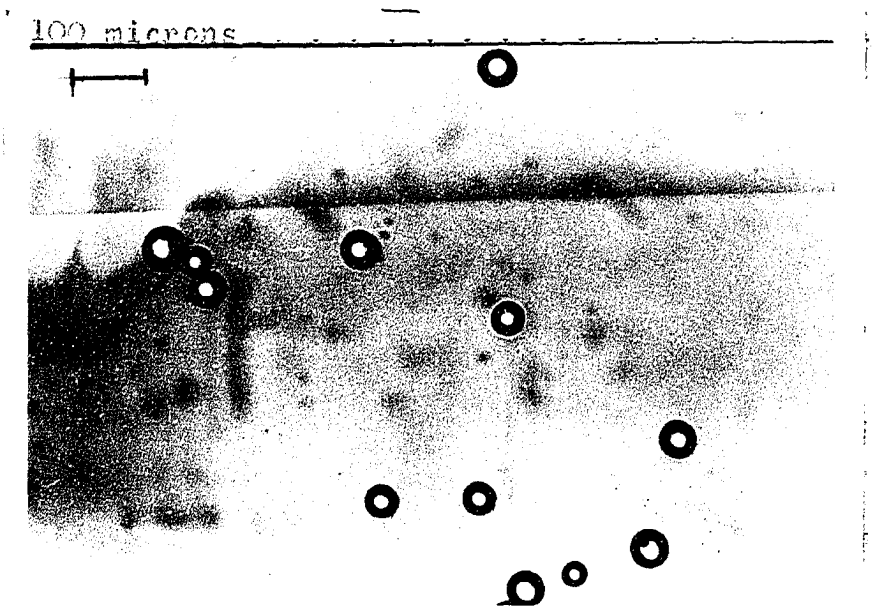
Pearce has shown that the size distribution for a system of spheres would influence the effective dielectric constant, other things being kept equal. This variable entering into the distribution function would

exert its influence on K, among other factors, as the smaller particles may fit in the spaces between the large ones.

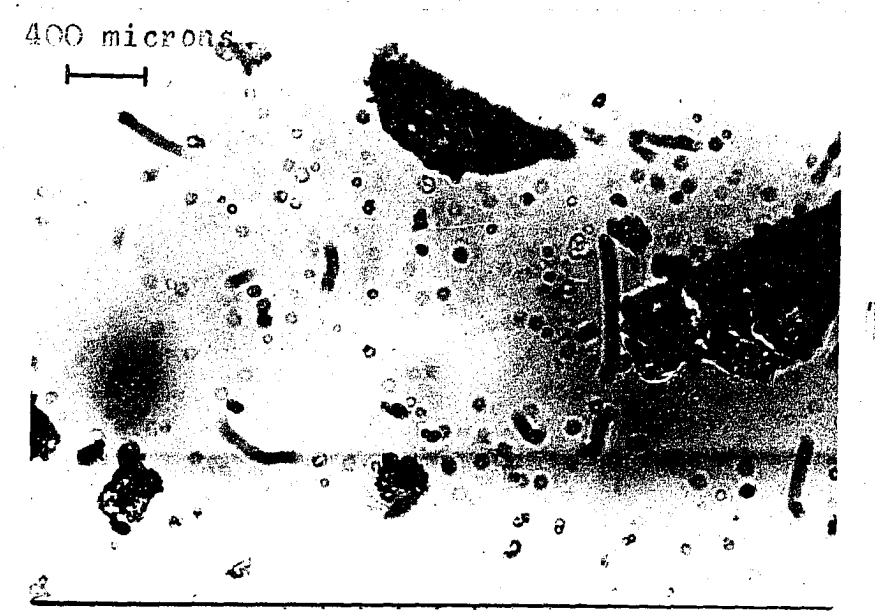
The value of K for a number of different substances were determined and this data is given in table XXV in the appendix.

In general there seems to be an inverse relationship between K and the volume fraction. However there are two factors involved, i.e. the volume fraction and the spatial arrangement of the particles. In Pearce's paper the majority of the data presented is that from Van Vessem and Bijvoet (21) where α is varied but varied in such a way that the particles are randomly distributed for the entire volume fraction range examined (eg. KCl in a liquid suspension). In dry powders a low value of the volume fraction implies agglomeration. In such cases Pearce's empirical equation might not work, i.e. "v" might depend on spatial distribution. Table XXV suggests that K depends on the volume fraction but in fact it may rather depend on the extent of agglomeration. Certainly asphericity does not seem to have a pronounced effect, (figures 5 through 8, photo micrographs) nor does particle size (glass beads). The powders all showed considerable agglomeration except for the glass beads and the ground glass.

In performing calculations such as these it was found that some equations were duplications. (Equations 17 and 34, 19 and 33, 13a and 22). Pradham and Gupta (32) were apparently not aware that the equations developed by them (33 and 34) were exactly those developed by Wiener (14) and Bottcher (17). Similarly Polder and Van Santen's (20) equation [22] is similar to that proposed earlier by Wagner (11).



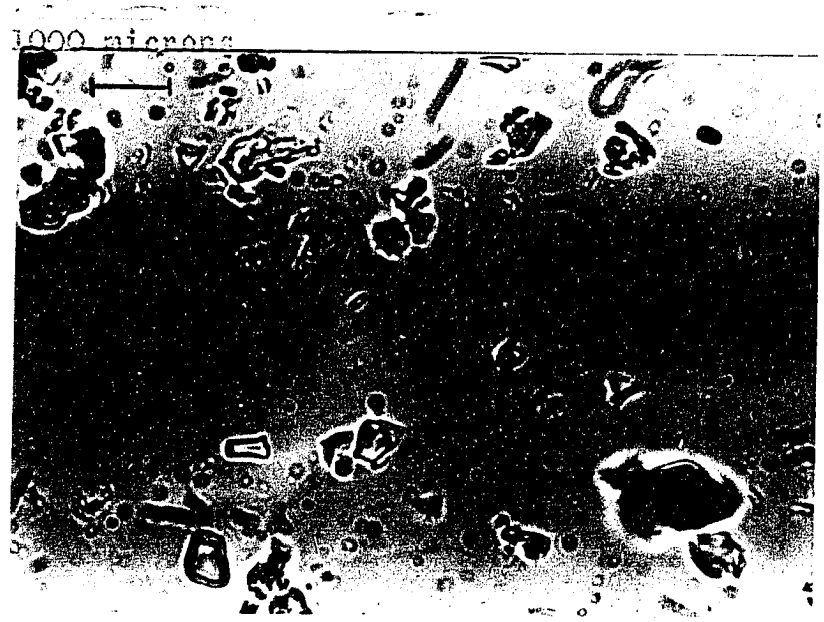
Glass Beads (.005 cm. dia.) in 35% Polyvinylpyrrolidone



Ground Glass (16 mesh) in 35% Polyvinylpyrrolidone

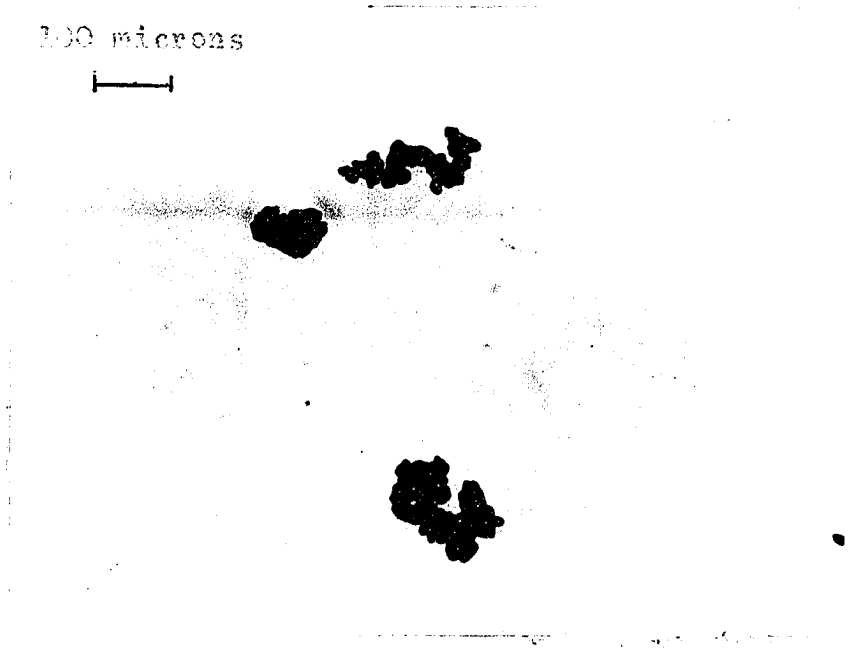
Figure 5.

Ground Glass (60 mesh) in 35% polyvinylpyrrolidone

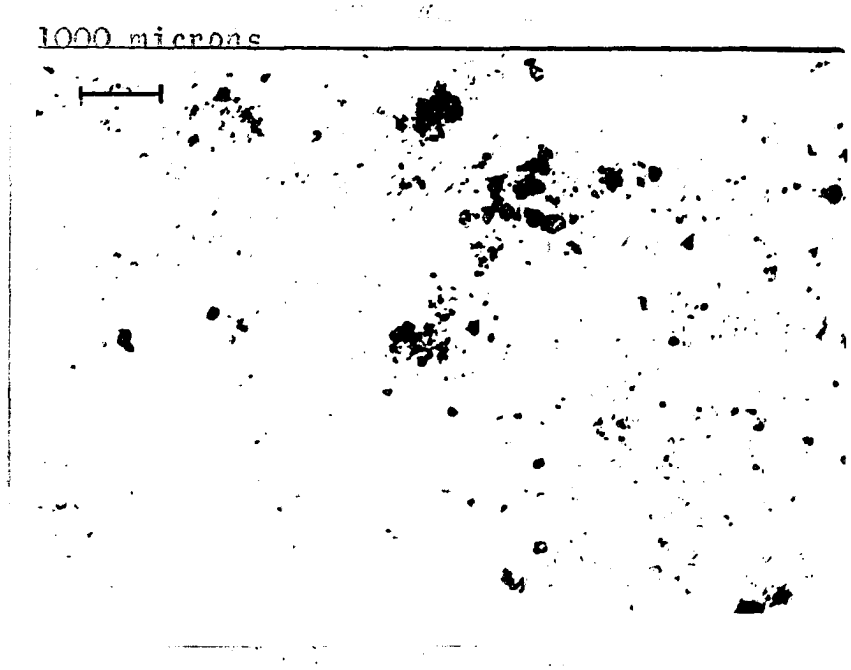


Silica Powder

Figure 6.



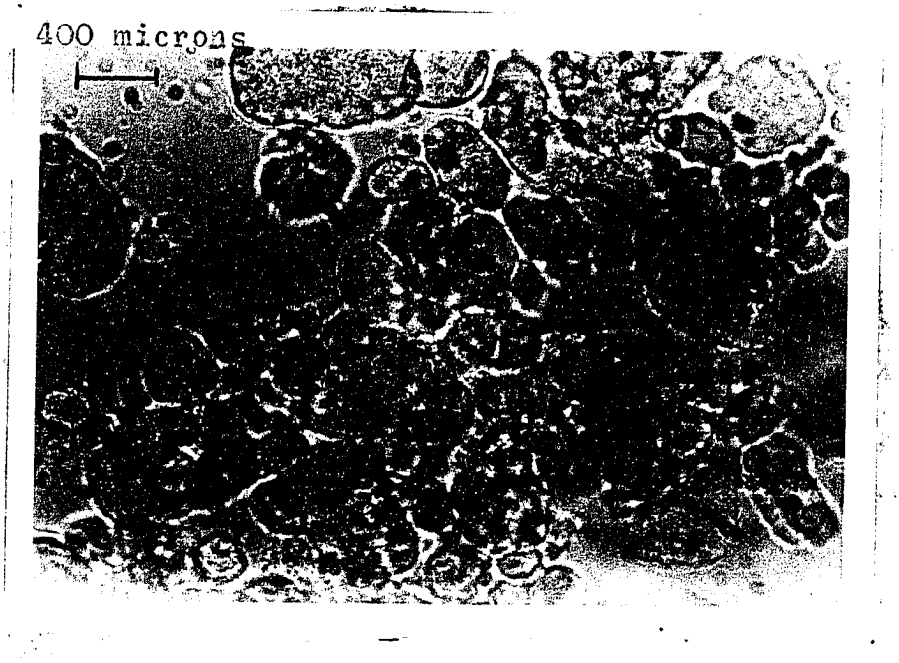
Sulphur in 35% polyvinylpyrrolidone



Calcium Carbonate in 35% polyvinylpyrrolidone

Figure 7.

Barium Sulphate in 35% polyvinylpyrrolidone



Fine Silica Powder in 35% polyvinylpyrrolidone

Figure 8.

Summary

It seems that particle size is not important in determining the calculated or experimental value of the dielectric constant of a powder. Most of the equations tested are valid for the low values of $\varepsilon_1/\varepsilon_2$ ($\varepsilon_1/\varepsilon_2 > 2$). According to the calculations performed employing equations 39, 13, 16, 17, 18, 19, 35, 22, 37, 38, 40 and 30, Bruggeman's equation works best for $\varepsilon_1/\varepsilon_2 < 5$. Higuchi's equation for $\sigma = 0.6$ seems to work for $K \simeq 0.35 - 0.40$ in the absence of agglomeration. For lower values of the volume fraction where agglomeration may be taking place, Higuchi's equation [30] requires larger values of K. Hence the value of the constant K appears to be a function of the volume fractions. This is exemplified in figure 9 when the falues K and σ in table XXV are plotted.

Variation of Higuchi's (23a) Constant K with Volume Fraction

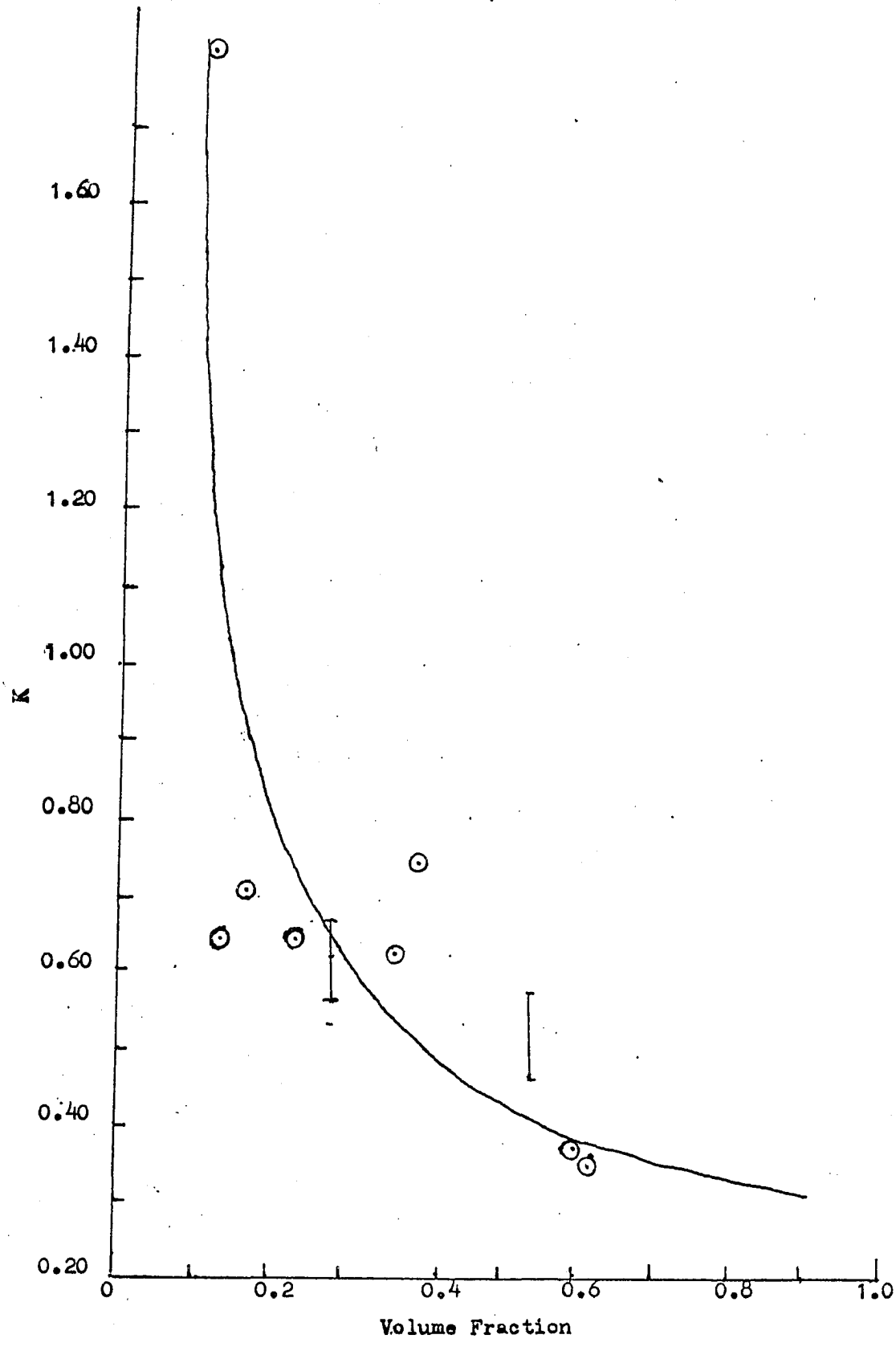


Figure 9.

V - APPENDIX

Table IV

EXPERIMENTAL VALUES

Cell number 2
Material Glass Beads (diameter) 0.03810 cm
Volume Fraction 0.6260
Dielectric constant determined graphically 7.51

Continuous Medium	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
Capacitance reading	2888	4669	4948	5077	5508
Effective dielectric constant	3.48	6.27	6.87	7.17	8.28

CALCULATED VALUES

EQUATION	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
39	6.788	8.231	8.004	7.823	5.504
13	8.827	7.300	7.417	7.474	7.165
16	16.285	7.384	7.437	7.480	7.225
17	5.517	7.260	7.411	7.473	7.196
18	6.724	7.286	7.415	7.474	7.174
19	5.867	7.273	7.413	7.473	7.183
33	5.867	7.273	7.413	7.473	7.183
34	5.517	7.260	7.411	7.473	7.196
35	5.733	7.269	7.413	7.473	7.186
13a	-11.358	7.605	7.488	7.494	7.358
37	5.753	7.415	7.566	7.630	7.348
38	6.026	7.312	7.451	7.512	7.221
22	-11.358	7.605	7.488	7.494	7.358
40	6.262	7.276	7.413	7.473	7.183
26	5.932	7.272	7.413	7.473	7.185
30 K=.90	6.029	7.279	7.414	7.473	7.177
30 K=.78	6.270	7.282	7.414	7.475	7.175
30 K=.40	7.197	7.291	7.415	7.474	7.170
30 K=.35	7.353	7.292	7.416	7.474	7.169
30 K=.30	7.520	7.293	7.416	7.474	7.169

Table V

EXPERIMENTAL VALUES

Cell number: 1
Material Glass Beads (diameter) 0.04699 cm
Volume Fraction: 0.6100
Dielectric constant determined graphically:7.45

Continuous Medium	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
Capacitance reading	2718	4458	4718	4854	5246
Effective dielectric constant	3.42	6.24	6.83	7.16	8.32

CALCULATED VALUES

EQUATION	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
39	6.845	8.278	7.976	7.839	5.432
13	9.192	7.321	7.387	7.479	7.150
16	18.523	7.411	7.407	7.485	7.213
17	5.548	7.278	7.381	7.478	7.183
18	6.867	7.307	7.385	7.478	7.159
19	5.942	7.293	7.383	7.478	7.169
33	5.942	7.293	7.383	7.478	7.169
34	5.548	7.278	7.381	7.478	7.183
35	5.788	7.289	7.383	7.478	7.173
13a	-11.305	7.623	7.453	7.499	7.340
37	5.805	7.422	7.522	7.621	7.319
38	6.098	7.329	7.418	7.513	7.204
22	-11.305	7.623	7.453	7.499	7.340
40	6.378	7.296	7.384	7.478	7.169
26	5.994	7.292	7.383	7.478	7.171
30 K=.90	6.089	7.298	7.384	7.478	7.163
30 K=.78	6.346	7.302	7.384	7.478	7.161
30 K=.40	7.353	7.311	7.385	7.478	7.156
30 K=.35	7.525	7.312	7.386	7.478	7.155
30 K=.30	7.710	7.314	7.386	7.478	7.154

Table VI

EXPERIMENTAL VALUES

Cell number : 4
Material : Glass Beads (diameter) 0.02032 cm
Volume Fraction: 0.6250
Dielectric constant determined graphically: 7.58

Continuous Medium	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
Capacitance reading	2943	4756	5052	5168	5670
Effective dielectric constant	3.52	6.28	6.89	7.14	8.39

CALCULATED VALUES

EQUATION	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
39	6.894	8.261	8.055	7.756	5.751
13	9.129	7.323	7.453	7.426	7.323
16	17.524	7.409	7.475	7.431	7.378
17	5.602	7.281	7.447	7.425	7.349
18	6.866	7.309	7.451	7.426	7.331
19	6.965	7.295	7.449	7.425	7.339
33	5.965	7.295	7.449	7.425	7.339
34	5.602	7.281	7.447	7.425	7.349
35	5.825	7.291	7.449	7.425	7.342
13a	-10.720	7.634	7.528	7.444	7.498
37	5.844	7.437	7.602	7.580	7.505
38	6.130	7.334	7.487	7.464	7.377
22	-10.720	7.634	7.528	7.444	7.498
40	6.384	7.298	7.450	7.425	7.338
26	6.033	7.295	7.449	7.425	7.340
30 K=.90	6.133	7.301	7.450	7.425	7.334
30 K=.78	6.386	7.304	7.450	7.425	7.332
30 K=.40	7.369	7.303	7.452	7.426	7.328
30 K=.35	7.535	7.315	7.452	7.426	7.327
30 K=.30	7.714	7.316	7.452	7.426	7.327

Table VII

EXPERIMENTAL VALUES

Cell number : 5
Material Glass Beads (diameter) 0.01473 cm
Volume Fraction: .6123
Dielectric constant determined graphically : 7.46

Continuous Medium	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
Capacitance reading	2917	4569	4825	4940	5342
Effective dielectric constant	3.53	6.25	6.84	7.13	8.24

CALCULATED VALUES

EQUATION	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
39	7.084	8.287	7.992	7.762	5.261
13	9.883	7.330	7.399	7.425	7.039
16	21.878	7.420	7.420	7.431	7.106
17	5.743	7.287	7.394	7.425	7.076
18	7.182	7.315	7.397	7.425	7.050
19	6.161	7.302	7.396	7.425	7.061
33	6.161	7.302	7.396	7.425	7.061
34	5.743	7.287	7.394	7.425	7.076
35	5.996	7.298	7.395	7.425	7.064
13a	-9.936	7.635	7.467	7.443	7.243
37	6.011	7.432	7.536	7.568	7.210
38	6.331	7.338	7.431	7.460	7.095
22	-9.936	7.635	7.467	7.443	7.243
40	6.649	7.305	7.396	7.425	7.060
26	6.223	7.301	7.396	7.425	7.063
30 K=.90	6.323	7.307	7.396	7.425	7.054
30 K=.78	6.608	7.311	7.397	7.425	7.052
30 K=.40	7.740	7.320	7.398	7.425	7.046
30 K=.35	7.936	7.321	7.398	7.425	7.045
30 K=.30	8.148	7.321	7.398	7.425	7.044

Table VIII

EXPERIMENTAL VALUES

Cell number : 6
Material Glass Beads (diameter) 0.01143 cm
Volume Fraction : .6177
Dielectric constant determined graphically 7.63

Continuous Medium	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
Capacitance reading	2817	4567	4850	4963	5427
Effective dielectric constant	3 3.51	6.31	6.93	7.19	8.42

CALCULATED VALUES

EQUATION	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
39	6.959	8.384	8.180	7.890	5.754
13	9.411	7.412	7.539	7.518	7.337
16	19.110	7.506	7.564	7.525	7.392
17	5.647	7.365	7.532	7.517	7.364
18	6.983	7.396	7.537	7.518	7.345
19	6.035	7.381	7.535	7.517	7.353
33	6.035	7.381	7.535	7.517	7.353
34	5.647	7.365	7.532	7.517	7.364
35	5.884	7.377	7.534	7.517	7.355
13a	-10.478	7.742	7.623	7.540	7.508
37	5.901	7.518	7.683	7.668	7.513
38	6.201	7.419	7.572	7.555	7.390
22	-10.478	7.742	7.623	7.540	7.508
40	6.482	7.384	7.535	7.517	7.352
26	6.099	7.380	7.535	7.517	7.354
30 K=.90	6.198	7.387	7.536	7.517	7.348
30 K=.78	6.464	7.391	7.536	7.518	7.346
30 K=.40	7.504	7.401	7.538	7.518	7.342
30 K=.35	7.682	7.403	7.538	7.518	7.341
30 K=.30	7.874	7.404	7.538	7.518	7.341

Table IX

EXPERIMENTAL VALUES

Cell number : 1
Material Glass Beads (Diameter) 0.0091 cm
Volume Fraction : 0.6238
Dielectric constant determined graphically : 7.46

Continuous Medium	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
Capacitance reading	2826	4494	4705	4852	5242
Effective dielectric constant	3.55	6.32	6.80	7.15	8.22

CALCULATED VALUES

EQUATION	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
39	6.977	8.363	7.848	7.787	5.343
13	9.377	7.401	7.303	7.444	7.067
16	18.634	7.492	7.320	7.449	7.131
17	5.667	7.355	7.299	7.443	7.101
18	6.980	7.385	7.302	7.443	7.077
19	6.043	7.370	7.300	7.443	7.087
33	6.043	7.370	7.300	7.443	7.087
34	5.667	7.355	7.299	7.443	7.101
35	5.898	7.366	7.300	7.443	7.091
13a	-10.283	7.731	7.362	7.462	7.271
37	5.915	7.512	7.450	7.598	7.249
38	6.212	7.420	7.337	7.481	7.124
22	-10.283	7.731	7.362	7.462	7.271
40	6.481	7.373	7.300	7.4430	7.087
26	6.113	7.370	7.300	7.443	7.089
30 K=.90	6.214	7.377	7.301	7.443	7.081
30 K=.78	6.478	7.380	7.301	7.443	7.079
30 K=.40	7.506	7.390	7.302	7.443	7.073
30 K=.35	7.682	7.391	7.302	7.443	7.072
30 K=.30	7.870	7.393	7.302	7.443	7.071

Table X

EXPERIMENTAL VALUES

Cell number : 2
Material Glass Beads (diameter) 0.00838 cm.
Volume Fraction : 0.6207
Dielectric constant determined graphically: 7.47

Continuous Medium	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
Capacitance reading	2902	4684	4911	5067	5500
Effective dielectric constant	3.50	6.30	6.78	7.14	8.26

CALCULATED VALUES

EQUATION	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
39	6.897	8.338	7.812	7.765	5.406
13	9.192	7.379	7.276	7.431	7.112
16	17.977	7.470	7.292	7.436	7.175
17	5.601	7.334	7.272	7.430	7.145
18	6.888	7.363	7.274	7.431	7.122
19	5.974	7.349	7.273	7.430	7.132
33	5.974	7.349	7.273	7.430	7.132
34	5.601	7.334	7.272	7.430	7.145
35	5.829	7.345	7.273	7.430	7.135
13a	-10.773	7.702	7.332	7.449	7.310
37	5.847	7.488	7.420	7.582	7.291
38	6.137	7.388	7.310	7.468	7.168
22	-10.773	7.702	7.332	7.449	7.310
40	6.401	7.352	7.273	7.430	7.131
26	6.039	7.348	7.273	7.430	7.133
30 K=.90	6.137	7.355	7.274	7.430	7.125
30 K=.78	6.394	7.358	7.274	7.430	7.123
30 K=.40	7.391	7.368	7.275	7.431	7.118
30 K=.35	7.561	7.370	7.275	7.431	7.117
30 K=.30	7.743	7.371	7.275	7.431	7.116

Table XI

EXPERIMENTAL VALUES

Cell number : 4
Material Glass Beads (diameter) 0.00660 cm
Volume Fraction : .6247
Dielectric constant determined graphically: 7.50

Continuous Medium	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
Capacitance reading	2958	4788	5004	5169	5635
Effective dielectric constant	3.54	6.34	6.78	7.15	8.29

CALCULATED VALUES

EQUATION	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
39	6.941	8.402	7.797	7.779	5.517
13	9.260	7.432	7.267	7.442	7.175
16	18.075	7.426	7.283	7.448	7.235
17	5.639	7.386	7.263	7.441	7.206
18	6.927	7.416	7.266	7.442	7.184
19	6.008	7.401	7.264	7.442	7.193
33	6.008	7.401	7.264	7.442	7.193
34	5.639	7.386	7.263	7.441	7.206
35	5.866	7.397	7.264	7.442	7.196
13a	-10.458	7.772	7.323	7.461	7.366
37	5.889	7.544	7.414	7.597	7.357
38	6.175	7.441	7.302	7.480	7.231
22	-10.458	7.772	7.323	7.461	7.366
40	6.437	7.404	7.265	7.442	7.193
26	6.078	7.400	7.264	7.442	7.195
30 K=.90	6.178	7.407	7.265	7.442	7.187
30 K=.78	6.437	7.411	7.265	7.442	7.186
30 K=.40	7.444	7.421	7.266	7.442	7.180
30 K=.35	7.615	7.423	7.266	7.442	7.180
30 K=.30	7.798	7.424	7.266	7.442	7.179

Table XII

EXPERIMENTAL VALUES

Cell number : 5
Material : Class Beads (diameter) 0.00508
Volume Fraction : .6383
Dielectric constant determined graphically : 7.46

Continuous Medium	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
Capacitance reading	2918	4601	4794	4946	5343
Effective dielectric constant	3.53	6.32	6.77	7.14	8.25

CALCULATED VALUES

EQUATION	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
39	6.760	8.260	7.727	7.727	5.555
13	8.604	7.334	7.223	7.410	7.175
16	15.050	7.417	7.238	7.415	7.233
17	5.503	7.293	7.220	7.409	7.205
18	6.637	7.319	7.222	7.410	7.184
19	5.824	7.306	7.221	7.410	7.193
33	5.824	7.306	7.221	7.410	7.193
34	5.503	7.293	7.220	7.409	7.205
35	5.703	7.302	7.221	7.410	7.196
13a	-11.321	7.654	7.277	7.427	7.370
37	5.725	7.457	7.380	7.575	7.368
38	5.985	7.347	7.261	7.450	7.233
22	-11.321	7.654	7.277	7.427	7.370
40	6.189	7.309	7.221	7.410	7.193
26	5.898	7.306	7.221	7.410	7.194
30 K=.90	5.996	7.312	7.222	7.410	7.187
30 K=.78	6.227	7.315	7.222	7.410	7.185
30 K=.40	7.102	7.324	7.223	7.410	7.180
30 K=.35	7.248	7.325	7.223	7.410	7.180
30 K=.30	7.403	7.327	7.223	7.410	7.179

Table XIII

EXPERIMENTAL VALUES

Cell number : 6
Material : Glass Beads (diameter) 0.00381 cm
Volume Fraction : 0.6162
Dielectric constant determined graphically : 7.54

Continuous Medium	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
Capacitance reading	2736	4534	4772	4937	5430
Effective dielectric constant	3.41	6.24	6.75	7.13	8.42

CALCULATED VALUES

EQUATION	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
39	6.746	8.233	7.760	7.752	5.734
13	8.836	7.293	7.235	7.420	7.328
16	16.722	7.378	7.251	7.426	7.384
17	5.474	7.251	7.231	7.420	7.355
18	6.710	7.278	7.234	7.420	7.336
19	5.842	7.265	7.233	7.420	7.344
33	5.842	7.265	7.233	7.420	7.344
34	5.474	7.251	7.231	7.420	7.355
35	5.699	7.261	7.232	7.420	7.347
13a	-11.864	7.590	7.288	7.438	7.500
37	5.719	7.399	7.375	7.567	7.502
38	5.995	7.302	7.268	7.456	7.381
22	-11.864	7.590	7.288	7.438	7.500
40	6.247	7.268	7.233	7.420	7.344
26	5.897	7.264	7.233	7.420	7.346
30 K=.90	5.991	7.271	7.233	7.420	7.339
30 K=.78	6.233	7.274	7.234	7.420	7.338
30 K=.40	7.170	7.283	7.234	7.420	7.333
30 K=.35	7.329	7.284	7.235	7.420	7.332
30 K=.30	7.498	7.285	7.235	7.420	7.332

Table XIV

EXPERIMENTAL VALUES

Cell number : 1
Material : Glass Beads (diameter) 50/50 mixture of 0.00279 + .04699
Volume Fraction : .7166
Dielectric constant determined graphically : 7.32

Continuous Medium	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
Capacitance reading	3447	4601	4762	4857	5114
Effective dielectric constant	4.41	6.56	6.94	7.17	7.85

CALCULATED VALUES

EQUATION	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
39	7.682	8.248	7.822	7.640	5.441
13	9.625	7.379	7.329	7.370	6.967
16	15.542	7.446	7.343	7.373	7.019
17	6.280	7.345	7.326	7.369	7.996
18	7.362	7.365	7.328	7.369	6.997
19	6.511	7.353	7.326	7.369	6.987
33	6.511	7.353	7.326	7.369	6.987
34	6.280	7.345	7.326	7.369	6.996
35	6.430	7.351	7.326	7.369	6.989
13a	-7.125	7.759	7.401	7.387	7.213
37	6.462	7.544	7.527	7.573	7.196
38	6.720	7.405	7.376	7.419	7.034
22	-7.125	7.759	7.401	7.387	7.213
40	6.746	7.354	7.327	7.369	6.986
26	6.665	7.355	7.327	7.369	6.986
30 K=.90	6.797	7.361	7.327	7.369	6.979
30 K=.78	7.055	7.363	7.328	7.369	6.977
30 K=.40	8.023	7.371	7.328	7.369	6.972
30 K=.35	8.182	7.372	7.328	7.369	6.971
30 K=.30	8.351	7.373	7.328	7.369	6.971

Table XV

EXPERIMENTAL VALUES

Cell number : 2
Material : Ca CO_3
Volume Fraction : 0.3615
Dielectric constant determined graphically : 9.33

Continuous Medium	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
Capacitance reading	2001	4723	5096	5330	6000
Effective dielectric constant	2.54	6.38	7.21	7.80	9.82

CALCULATED VALUES

EQUATION	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
39	9.071	13.080	12.256	12.550	7.529
13	45.646	10.211	9.739	10.110	8.912
16	-10.913	10.947	10.000	10.310	8.933
17	6.312	7.730	9.605	10.020	8.916
18	12.891	10.092	9.710	10.092	8.913
19	8.684	9.987	9.683	10.074	8.914
33	8.684	9.987	9.683	10.074	8.914
34	6.312	9.730	9.605	10.020	8.916
35	7.269	9.899	9.659	10.058	8.914
13a	-9.176	11.062	10.038	10.338	8.936
37	8.136	9.678	9.351	9.722	8.559
38	8.145	9.871	9.588	9.978	8.824
22	-9.176	11.062	10.038	10.338	8.936
40	9.273	9.981	9.680	10.072	8.914
26	7.578	9.890	9.654	10.055	8.915
30 K=.90	7.468	9.918	9.665	10.063	8.914
30 K=.78	8.175	9.956	9.676	10.070	8.914
30 K=.40	12.177	10.075	9.706	10.090	8.913
30 K=.35	13.177	10.091	9.710	10.092	8.913
30 K=.30	14.415	10.108	9.714	10.095	8.913

Table XVI

EXPERIMENTAL VALUES

Cell number : 4
Material : Ground Glass 16 mesh
Volume Fraction : .6010
Dielectric constant determined graphically: 3.56

Continuous Medium	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
Capacitance reading	1791	3511	3842	3993	4491
Effective dielectric constant	2.34	4.24	4.71	4.94	5.78

CALCULATED VALUES

EQUATION	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
39	4.301	3.420	2.792	2.393	-.923
13	4.169	3.891	3.940	3.942	3.418
16	5.015	3.902	3.987	4.015	3.714
17	3.507	3.894	3.968	3.996	3.838
18	3.849	3.892	3.948	3.957	3.539
19	3.643	3.893	3.956	3.973	3.667
33	3.643	3.893	3.956	3.973	3.667
34	3.507	3.894	3.968	3.996	3.838
35	3.595	3.893	3.959	3.978	3.707
13a	9.683	3.924	4.075	4.150	4.239
37	3.630	3.966	4.035	4.055	3.760
38	3.690	3.911	3.974	3.990	3.668
22	9.682	3.924	4.075	4.150	4.239
40	3.720	3.893	3.956	3.973	3.675
26	3.644	3.893	3.958	3.977	3.702
30 K=.90	3.683	3.893	3.951	3.963	3.572
30 K=.78	3.739	3.892	3.950	3.960	3.551
30 K=.40	3.925	3.892	3.945	3.951	3.488
30 K=.35	3.953	3.892	3.944	3.950	3.479
30 K=.30	3.981	3.892	3.944	3.949	3.470

Table XVII

EXPERIMENTAL VALUES

Cell number: 5
Material : Ground Glass 60 mesh
Volume Fraction : .6437
Dielectric constant determined graphically: 3.49

Continuous Medium	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
Capacitance reading	2283	3442	3684	3822	4285
Effective dielectric constant	2.81	4.24	4.61	4.83	5.67

CALCULATED VALUES

EQUATION	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
39	5.071	3.540	2.848	2.518	-.188
13	5.217	3.948	3.921	3.946	3.638
16	6.624	3.957	3.963	4.011	3.887
17	4.149	3.951	3.946	3.994	3.980
18	4.637	3.949	3.928	3.961	3.743
19	4.310	3.950	3.937	3.976	3.854
33	4.310	3.950	3.937	3.976	3.854
34	4.149	3.951	3.946	3.994	3.980
35	4.254	3.950	3.939	3.980	3.884
13a	45.508	3.979	4.067	4.167	4.459
37	4.294	4.044	4.037	4.081	3.989
38	4.393	3.973	3.958	3.997	3.856
22	45.508	3.979	4.067	4.167	4.459
40	4.437	3.950	3.936	3.975	3.853
26	4.338	3.950	3.937	3.978	3.870
30 K=.90	4.395	3.949	3.931	3.965	3.762
30 K=.78	4.485	3.949	3.929	3.962	3.745
30 K=.40	4.793	3.949	3.925	3.955	3.694
30 K=.35	4.839	3.949	3.925	3.954	3.687
30 K=.30	4.887	3.949	3.924	3.953	3.680

Table XVIII

EXPERIMENTAL VALUES

Cell number : 5
Material $BaSO_4$
Volume Fraction : .2305
Dielectric constant determined graphically ≈ 11.00

Continuous Medium	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
Capacitance reading	1418	4493	4908	5170	6017
Effective dielectric constant	2.01	6.09	7.05	7.74	10.67

CALCULATED VALUES

EQUATION	Vacuum	Chloroform	Ethyl Acetate	Methyl Acetate	Dichloro-Ethane
39	14.854	22.495	20.148	21.220	14.612
13	-35.205	12.757	11.523	12.249	11.748
16	-5.419	14.904	12.254	12.915	11.772
17	6.703	11.412	11.095	11.870	11.744
18	35.227	12.501	11.457	12.192	11.747
19	14.240	12.274	11.394	12.137	11.747
33	14.240	12.274	11.394	12.137	11.747
34	6.703	11.412	11.095	11.870	11.744
35	8.401	11.921	11.291	12.047	11.746
13a	-8.558	13.921	11.940	12.631	11.762
37	0	11.709	10.582	11.249	10.744
38	10.108	11.841	11.108	11.842	11.487
22	-8.558	13.921	11.940	12.631	11.762
40	12.483	12.285	11.403	12.145	11.747
26	8.726	11.845	11.256	12.015	11.745
30 K=.90	8.271	11.859	11.271	12.030	11.746
30 K=.78	9.365	11.967	11.305	12.059	11.746
30 K=.40	17.833	12.319	11.407	12.149	11.747
30 K=.35	-	12.369	11.421	12.161	11.747
30 K=.30	-	12.421	11.435	12.173	11.747

Table XXI

Summary Table of the Calculated Values for the Glass Beads with Ethyl Acetate as a Medium.

Bead Size (Cm.dia)	.0381	.0470	.0203	.0147	.0114	.0099	.0084	.0066	.0051	.0038
Dielectric Constant	7.51	7.45	7.58	7.46	7.63	7.46	7.47	7.50	7.46	7.54
Effective Dielectric Constant	6.87	6.83	6.89	6.84	6.93	6.80	6.78	6.78	6.77	6.75
39	8.004	7.976	8.055	7.992	8.180	7.848	7.812	7.797	7.727	7.760
13	7.417	7.387	7.453	7.399	7.539	7.303	7.276	7.267	7.223	7.235
16	7.437	7.407	7.475	7.420	7.564	7.320	7.292	7.283	7.238	7.251
17	7.411	7.381	7.447	7.394	7.532	7.299	7.272	7.263	7.220	7.231
18	7.415	7.385	7.451	7.397	7.537	7.302	7.274	7.266	7.220	7.234
19	7.413	7.383	7.449	7.396	7.535	7.300	7.273	7.264	7.221	7.233
35	7.413	7.383	7.449	7.395	7.534	7.300	7.273	7.264	7.221	7.232
22	7.488	7.453	7.528	7.467	7.623	7.362	7.332	7.323	7.277	7.288
37	7.566	7.522	7.602	7.536	7.683	7.450	7.420	7.414	7.380	7.375
38	7.451	7.418	7.487	7.431	7.572	7.337	7.310	7.302	7.261	7.268
40	7.413	7.384	7.450	7.396	7.535	7.300	7.273	7.265	7.221	7.233
30 K=.90	7.414	7.384	7.450	7.396	7.536	7.301	7.274	7.265	7.222	7.233
30 K=.78	7.414	7.384	7.450	7.397	7.536	7.301	7.274	7.265	7.222	7.234
30 K=.40	7.415	7.385	7.452	7.398	7.538	7.302	7.275	7.266	7.223	7.234
30 K=.35	7.416	7.386	7.452	7.398	7.538	7.302	7.275	7.266	7.223	7.235
30 K=.30	7.416	7.386	7.452	7.398	7.538	7.302	7.275	7.266	7.223	7.235

EQUATIONS

Table XIX

Summary Table of the Calculated Values for the Glass Beads with Vacuum as a Medium.

Bead Size (Cm.dia)	.0381	.0470	.0203	.0147	.0114	.0099	.0084	.0066	.0051	.0038
Dielectric Constant	7.51	7.45	7.58	7.46	7.63	7.46	7.47	7.50	7.46	7.54
Effective Dielectric Constant	3.48	3.42	3.52	3.53	3.51	3.55	3.50	3.54	3.53	3.41
39	6.788	6.875	6.894	7.084	6.959	6.977	6.897	6.941	6.760	6.746
13	8.827	9.192	9.129	9.883	9.411	9.377	9.192	9.260	8.604	8.836
16	16.285	18.523	17.524	21.878	19.110	18.634	17.977	18.075	15.050	16.722
17	5.517	5.548	5.602	5.743	5.647	5.667	5.601	5.639	5.503	5.474
18	6.724	6.867	6.816	7.182	6.983	6.980	6.888	6.927	6.637	6.710
19	5.867	5.942	5.965	6.161	6.035	6.043	5.974	6.008	5.824	5.842
35	5.733	5.788	5.825	5.996	5.884	5.898	5.829	5.886	5.703	5.699
22	-11.358	-11.305	-10.720	-9.936	-10.478	-10.283	-10.773	-10.458	-11.321	-11.864
37	5.753	5.805	5.844	6.011	5.901	5.915	5.847	5.884	5.725	5.719
38	6.026	6.098	6.130	6.331	6.201	6.212	6.137	6.175	5.985	5.995
40	6.262	6.378	6.384	6.649	6.482	6.481	6.401	6.437	6.189	6.247
30 K=.90	6.029	6.089	6.133	6.323	6.198	6.214	6.137	6.178	5.996	5.991
30 K=.78	6.270	6.346	6.386	6.608	6.464	6.478	6.394	6.437	6.227	6.233
30 K=.40	7.197	7.353	7.369	7.740	7.504	7.506	7.391	7.444	7.102	7.170
30 K=.35	7.353	7.525	7.535	7.936	7.682	7.682	7.561	7.615	7.248	7.329
30 K=.30	7.520	7.710	7.714	8.148	7.874	7.870	7.743	7.798	7.403	7.498

EQUATIONS

Table XXIII

Summary Table of the Calculated Values for the Glass Beads with Dichloro Ethane as a Medium.

Bead Size (Cm.dia)	.0381	.0470	.0203	.0147	.0114	.0099	.0084	.0066	.0051	.0038
Dielectric Constant	7.51	7.45	7.58	7.46	7.63	7.46	7.47	7.50	7.46	7.54
Effective Dielectric Constant	8.28	8.32	8.39	8.24	8.42	8.22	8.26	8.29	8.25	8.42
39	5.504	5.432	5.751	5.261	5.754	5.343	5.406	5.517	5.555	5.734
13	7.165	7.150	7.323	7.039	7.337	7.067	7.112	7.175	7.175	7.328
16	7.225	7.213	7.378	7.106	7.392	7.131	7.175	7.235	7.233	7.384
17	7.196	7.183	7.349	7.076	7.364	7.101	7.145	7.206	7.205	7.355
18	7.174	7.159	7.331	7.050	7.345	7.077	7.122	7.184	7.184	7.336
19	7.183	7.169	7.339	7.061	7.353	7.087	7.132	7.193	7.193	7.344
35	7.186	7.173	7.342	7.064	7.355	7.091	7.135	7.196	7.196	7.347
22	7.358	7.340	7.498	7.243	7.508	7.271	7.310	7.366	7.370	7.500
37	7.348	7.319	7.505	7.210	7.513	7.249	7.291	7.357	7.368	7.502
38	7.221	7.204	7.177	7.095	7.390	7.124	7.168	7.231	7.233	7.381
40	7.183	7.169	7.338	7.060	7.352	7.087	7.131	7.193	7.193	7.344
30 K=.90	7.177	7.163	7.334	7.054	7.348	7.081	7.125	7.187	7.187	7.339
30 K=.78	7.175	7.161	7.332	7.052	7.346	7.079	7.123	7.186	7.185	7.338
30 K=.40	7.170	7.156	7.328	7.046	7.342	7.073	7.118	7.180	7.180	7.333
30 K=.35	7.169	7.155	7.327	7.045	7.341	7.072	7.117	7.180	7.180	7.332
30 K=.30	7.169	7.154	7.327	7.044	7.341	7.071	7.116	7.179	7.179	7.333

EQUATIONS

Table XX

Summary Table of the Calculated Values for the Glass Beads with Chloroform as a Medium.

Bead Size (Cm.dia)	.0381	.0470	.0203	.0147	.0114	.0099	.0084	.0066	.0051	.0038
Dielectric Constant	7.51	7.45	7.58	7.46	7.63	7.46	7.47	7.50	7.46	7.54
Effective Dielectric Constant	6.27	6.24	6.28	6.25	6.31	6.32	6.30	6.34	6.32	8.24
39	8.231	8.278	8.261	8.287	8.384	8.363	8.338	8.402	8.260	8.233
13	7.300	7.321	7.323	7.330	7.412	7.401	7.379	7.432	7.334	7.293
16	7.384	7.411	7.409	7.420	7.506	7.492	7.470	7.526	7.417	7.378
17	7.260	7.278	7.281	7.287	7.365	7.355	7.334	7.386	7.293	7.251
18	7.286	7.307	7.309	7.315	7.396	7.385	7.363	7.416	7.319	7.278
19	7.273	7.293	7.295	7.302	7.381	7.370	7.349	7.401	7.306	7.265
35	7.269	7.289	7.291	7.298	7.377	7.366	7.345	7.397	7.302	7.261
22	7.605	7.623	7.634	7.635	7.742	7.731	7.702	7.772	7.654	7.590
37	7.415	7.422	7.437	7.432	7.518	7.512	7.488	7.544	7.457	7.399
38	7.312	7.329	7.334	7.338	7.419	7.420	7.388	7.441	7.347	7.302
40	7.276	7.296	7.298	7.305	7.384	7.373	7.352	7.404	7.309	7.268
30 K=.90	7.279	7.298	7.301	7.307	7.387	7.377	7.355	7.407	7.312	7.271
30 K=.78	7.282	7.302	7.304	7.311	7.391	7.380	7.358	7.411	7.315	7.274
30 K=.40	7.291	7.311	7.303	7.320	7.401	7.390	7.368	7.421	7.324	7.283
30 K=.35	7.292	7.312	7.315	7.320	7.403	7.391	9.370	7.423	7.325	7.284
30 K=.30	7.293	7.314	7.316	7.321	7.404	7.393	7.371	7.424	7.327	7.285

EQUATIONS

Table XXII

Summary Table of the Calculated Values for the Glass Beads with Methyl Acetate as a Medium.

Bead Size (Cm.dia)	.0381	.0470	.0203	.0147	.0114	.0099	.0084	.0066	.0051	.0038
Dielectric Constant	7.51	7.45	7.58	7.46	7.63	7.46	7.47	7.50	7.46	7.54
Effective Dielectric Constant	7.17	7.16	7.14	7.13	7.19	7.15	7.14	7.15	7.14	7.13
39	7.823	7.839	7.756	7.762	7.890	7.787	7.765	7.779	7.727	7.752
13	7.474	7.479	7.426	7.425	7.518	7.444	7.431	7.442	7.410	7.420
16	7.480	7.485	7.431	7.431	7.525	7.449	7.436	7.448	7.415	7.426
17	7.473	7.478	7.425	7.425	7.517	7.443	7.430	7.441	7.409	7.420
18	7.474	7.478	7.426	7.425	7.518	7.443	7.431	7.442	7.410	7.420
19	7.473	7.478	7.425	7.425	7.517	7.443	7.430	7.442	7.410	7.420
35	7.473	7.478	7.425	7.425	7.517	7.443	7.430	7.442	7.410	7.420
22	7.494	7.499	7.444	7.443	7.540	7.462	7.449	7.461	7.427	7.438
37	7.630	7.621	7.580	7.568	7.668	7.598	7.582	7.597	7.575	7.567
38	7.512	7.513	7.464	7.460	7.555	7.481	7.468	7.480	7.450	7.456
40	7.473	7.478	7.425	7.425	7.517	7.443	7.430	7.552	7.410	7.420
30 K=.90	7.473	7.478	7.425	7.425	7.517	7.443	7.430	7.442	7.410	7.420
30 K=.78	7.475	7.478	7.425	7.425	7.518	7.443	7.430	7.442	7.410	7.420
30 K=.40	7.474	7.478	7.426	7.425	7.518	7.443	7.431	7.442	7.410	7.420
30 K=.35	7.474	7.478	7.426	7.425	7.518	7.443	7.431	7.442	7.410	7.420
30 K=.30	7.474	7.478	7.426	7.425	7.518	7.443	7.431	7.442	7.410	7.420

EQUATIONS

TABLE XXIV

Calculated values of K

System	$\varepsilon_1/\varepsilon_2$	v (exptl.)	K (calc.)
Na Cl/oil	2.605	.375	-.3485
$K_2Al_2(SO_4)_4$/oil	2.835	.375	.0502
KCl/vac.	4.57	.350	1.0076
$PbCl_2$/vac.	28.00	.730	.7773 *
$PbCl_2/CCl_4$	12.56	.650	.6524
NaCl/air	5.81	.450	.7951
KCl/air	4.68	.390	.8691
$NH_4Cl/C\ Cl_4 - C\ Br_4$	3.13	.320	.8121
$KCl/C\ Cl_4 - C\ Br_4$	1.972	.180	1.3178
Ca CO_3/rubber	3.47	.375	.6007
Ca CO_3/Vistonex	3.87	.450	.2960
KCl/air	4.78	.350	1.0271
Powdered quartz/benzene	2.01	.150	1.8891
Powdered quartz/nitrobenzene	0.135	-.900	1.5866
TiO_2/air sintered at 1500°, 7 days	114	.500	.9992
TiO_2/air sintered 1000-1300°, 1 hour	114	.870	.8441
TiO_2/air unsintered	114	.905	.7669

* Higuchi's reference value

TABLE XXV

The effect of volume fraction, material and $\varepsilon_1/\varepsilon_2$ on the value of K.

Material	Volume Fraction	$\varepsilon_1/\varepsilon_2$	K
Silica (compressed)	0.119	≈3.81	1.80
TiO_2	0.133	≈100	.65
TiO_2	0.169	≈100	.71
$BaSO_4$	0.23	≈11	.65
S	0.28	≈4	.55
$CaCO_3$	0.36	9.33	.63
PbO	0.392	25.9	.74
Silica powder	0.539	≈3.81	.55
Ground Glass	.60→ .64	3.92	.40
Glass Beads	.62	7.50	.35

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